SOUTH FORK EEL TMDL: SEDIMENT SOURCE ANALYSIS

Final Report

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EXECUTIVE SUMMARY

Stillwater Sciences, under contract to Tetra Tech, completed a sediment source analysis for the South Fork Eel Basin (SFEB) to assist the U.S. Environmental Protection Agency with development of a sediment TMDL (Total Maximum Daily Load). This analysis included identifying sediment sources and estimating historical and current loading from various sediment sources in the SFEB. The size of the SFEB (1,783 km^2 [690 mi^2]), its complexity in terms of physical and biological conditions and land use history, access limitations (about 80% of the basin is in private ownership), a limited time frame, and budget constraints created substantial technical and logistical challenges to sediment source analysis. Given the constraints discussed above, we adopted an approach based on the following steps: (1) stratification of the watershed into geomorphic terrains (i.e., areas expected to have similar sediment production characteristics under reference and disturbed conditions), (2) analysis of existing data on sediment sources, (3) use of local intensive analysis (field data collection, sequential aerial photograph analysis) to estimate sediment production in representative portions of the SFEB, and (4) extrapolation of results from intensive analysis areas to the entire SFEB based on GIS/DTM methods.

A key purpose of this analysis was to estimate the role of anthropogenic contributions to overall sediment loading under current conditions and land use practices. Therefore, in addition to quantifying sediment sources according to discrete sediment production processes, we further characterized sediment sources as being of natural or anthropogenic origin and by proportion of fine (< 2 mm) and coarse (> 2 mm) sediment. A *sediment ratio approach*, based on the use of a ratio to compare the volume of sediment delivered from *anthropogenic sources* to that delivered from *natural sources*, was used to assess the potential impacts of land management activities on sediment inputs and as a quantitative indicator of hillslope processes. We believe that the ratio of anthropogenic to total sediment loading is a more meaningful numeric target than mean annual sediment yield, which (1) is highly variable under natural conditions due to climatic effects, (2) provides no information about the source of sediment, and (3) may fail to provide desired levels of protection and restoration when used as a numeric target. Using a sediment ratio rather than mean annual sediment yield as a hillslope indicator has the following potential advantages: (1) a ratio can be used as a numeric target that distinguishes the anthropogenic contribution to sediment loads and is less dependent on climatic conditions (i.e., natural variability between wet and dry periods) than mean annual load; (2) a ratio may capture the effects of chronic fine sediment production from roads during dry years; a mean annual sediment load approach would not capture such impacts; (3) a target ratio may be applicable in different watersheds with similar geology, hydrology, and lithology; and (4) a ratio may be more meaningful in a given year or period than an average total sediment load.

BACKGROUND/ PHYSIOGRAPHIC CONDITIONS

The SFEB occurs in the northern California Coast Range and has a drainage area of 1,783 km^2 (690 mi^2) (Maps 1, 2). Precipitation generally increases from south to north in the basin, with the highest average precipitation (115 inches/yr) occurring in the Bull Creek headwaters, and is higher on the west side of the watershed than on the east side (USBLM et al. 1996). Vegetation of the west side of the basin is dominated by redwood and Douglas-fir (and tanoak in second-growth forests), while the east side of the basin is mainly characterized by oak woodlands and grasslands with some conifers.

The SFEB is frequently cited as having among the highest erosion rates in North America (e.g., Cleveland 1977, James 1983, Lisle 1990). High erosion rates are attributable to a combination of widespread tectonic deformation of the underlying rocks, rapid uplift rates, steep topography, high precipitation rates, and widespread anthropogenic disturbances, particularly in the decades following World War II (e.g., Lisle 1990).

The geology of the SFEB is dominated by the Franciscan Complex, including rocks of the Coastal Belt, Yager, and Central Belt (Melange) terrains. Deeply weathered rocks of the Franciscan Complex are highly unstable, largely because of the presence of many large and small faults and shear zones, and high precipitation rates. Valleys in portions of the SFEB are filled with Quaternary alluvium, including stream terraces.

SEDIMENT SOURCE ANALYSIS METHODOLOGY

The sediment source assessment focused on quantifying sediment production in intensive study areas (ISAs) selected as part of the watershed stratification process. These results were then extrapolated to the whole SFEB using GIS/DTM-based methods. For each sediment source, magnitudes of sediment inputs from different source categories were estimated and a ratio of anthropogenic to total sediment production was calculated.

Watershed Stratification and Intensive Analysis

The sediment source analysis stratifies the SFEB to delineate areas expected to have similar geomorphic processes, response potential, and sediment yields. Lithology was used as the primary stratification criterion, based on the hypothesis that lithology has a dominant influence on sediment production and that the relative importance of different sediment transfer processes varies between terrains. Seismic activity (uplift), precipitation, topography and potential shallow landslide instability, and geography (location in the SFEB) were additional criteria used for stratification of the SFEB into geomorphic units.

This stratification divides the basin into four “geomorphic terrains” expected to have different sediment production characteristics and processes: (1) Melange terrain (Central Belt Franciscan), (2) Coastal Belt Franciscan terrain, (3) Yager terrain, and (4) “Alluvial terrain” (terraces and floodplain alluvium [i.e., stream channel and terrace deposits]). Geomorphic terrains are named after dominant geologic units, but they do not strictly follow geologic unit delineations. Areas were lumped together and geologic coverages were simplified to create “terrains” based on a combination of lithology and secondary stratification criteria, including geography, precipitation, topography. In addition to stratifying the watershed into geomorphic terrains, we delineated large inner gorge areas, which were hypothesized to be a substantial sediment source with a sediment-input contribution disproportionate to their extent.

Areas within each of the three major geomorphic terrains (Coastal Belt, Yager, Melange) were selected for intensive analysis in which sediment sources were quantified. Data collected in our ISAs were used as a basis for extrapolating sediment production estimates across the SFEB using DTM-based information

industrial forestry land use);
- Sproul Creek basin (representative of Coastal Belt and Yager areas with recent timber harvest activity)
- Tom Long Creek basin (representative of areas in the Melange and Coastal Belt terrains and of mixed land uses including dispersed residential, grazing, and non-industrial timber harvesting)
- Bull Creek basin (representative of the Yager terrain, high precipitation and uplift rates, and of a land use pattern characterized by substantial impacts followed by a "recovery" period).

Time Periods

The sediment source analysis presented here assessed three time periods: 1942–1965 (for the whole SFEB), 1966–1981 (for ISAs only), and 1981–1996 (for ISAs and the whole SFEB), with some variations in the length of time periods because of differences in source data. Our analysis largely focused on determining the magnitude of sediment sources and the ratio of anthropogenic to total inputs under current conditions, approximated by the 1981–1996 period. Sediment sources during previous time periods were evaluated to the extent possible using existing data. Assessment of sediment sources under current conditions relied on a combination of field surveys, mapping of shallow and active earthflows using 1994 and 1996 aerial photographs, and analysis of existing data. Sediment source assessments for the Bull Creek and Hollow Tree ISAs relied heavily on existing data, including preliminary results of a Level II watershed analysis by MRC (for the Hollow Tree ISA). Aerial photograph mapping of erosional features was carried out for the Tom Long and Sproul Creek basins using 1996 (1:24,000) and 1994 (1:12,000) photographs, respectively.

Sediment source assessments for the 1966–1981 time period relied on CDMG maps, skid trail erosion estimates based on analysis by MRC, and the assumption that sediment delivery from chronic processes (defined here as earthflows, soil creep, and road surface erosion) and from road crossing and gully erosion was the same as under current conditions (1981–1996). The California Division of Mines and Geology (CDMG) completed geomorphic mapping covering nearly the entire SFEB based on 1981 aerial photos. Assuming that aerial photographs represent an approximately 15-year period of record (most landslides revegetate within this time), results of this mapping served as a basis for assessing sediment production from landsliding for the period from 1966 to 1981. This undoubtedly underestimates sediment loading from landsliding because some landslides are likely unmapped and others may revegetate rapidly. The 1966–1981 period was wetter than the more recent period in the SFEB; analysis of USGS records from the SFE at Miranda gauge (Figure 2) indicated that average annual runoff was higher in the 1966–1981 period than in the 1981–1996 period.

A report by USDA (1970) includes a sediment source analysis of the SFEB for the 1942-1965 period, based on extensive aerial photograph and field surveys. The results of this report were summarized to provide insight into erosional processes from 1942 to 1965, representing a third time period in our analysis.

Sediment Source Categories and Assumptions Used in Source Analysis

Sediment sources were quantified according to the following source categories: shallow landslides, deep-seated landslides, soil creep, road surface erosion, road crossing and gullying erosion, and skid trails. A number of other possible categories, such as bank erosion and hillslope (non-road-related) surface erosion, were not quantified (see Section 3.5.7 for further discussion). Many assumptions were applied in developing estimates of sediment delivery from various sources, as described in the descriptions of source categories in Section 3.5 (sections in which each assumption is discussed are indicated below). The key assumptions are summarized below:

- All shallow landslides mapped on aerial photographs by Stillwater and CDMG are assumed to have an average depth of 1.3 m (Section 3.5.1).
- For shallow landslides, the relative proportion of natural versus anthropogenic landslides was estimated using the following criteria: (1) landslides associated with roads were identified as anthropogenic, (2) all non-road-related inner gorge slides were assumed to be natural, (3) all non-inner gorge streamside slides were assumed to be natural, (4) all upland slides were assumed to be anthropogenic. The errors in these assumptions (overestimating the anthropogenic contribution to upland landsliding and underestimating anthropogenic contributions to inner gorge and other streamside failures) may counterbalance each other, resulting in reasonable overall estimates of the ratio of anthropogenic:total loading (Section 3.5.1).
- Debris torrent tracks were converted from mapped length to volume assuming 8 m^3 of material removed per meter of torrent track (Benda and Cundy 1990). The resulting volumes for runouts (torrent tracks) were added to mapped scar volumes (Section 3.5.1).
- For estimating landslide sediment delivery during the 1966–1981 period, CDMG maps were used and assumed to represent that period. Stillwater Sciences assumed that individual features depicted as point slides delivered an average of 1,000 tons, based on average assumed point slide area of 400 m^2, depth of 1.3 m, and bulk density of 1.9 t/m^3. For polygon features, area was estimated using the Stillwater Sciences GIS, and a delivery ratio of 100% was assumed (Section 3.5.1).
- Earthflows were assumed to move at a rate of 1 m/yr and to have average toe heights of 9 m. Earthflow sediment delivery was calculated as follows: (average movement rate [1 m/yr]) * (average toe height [9 m]) * (length of toe [as determined by mapping]). Sediment delivery by this calculation was assumed to incorporate gullies associated with earthflows. Translational/rotational deep-seated landslides in the SFEB were assumed to be dormant (Section 3.5.2).
- Road surface erosion was calculated using a GIS-based model, SEDMODL, based on Washington DNR methods (Section 3.5.3, Appendix B).
- Road crossing and gully erosion was calculated by multiplying an average unit-length rate of road crossing and gully erosion of 82 t/km/yr (as determined in the field from limited surveys) by non-ridge road length in a given subbasin (Section 3.5.4).
- Skid trail erosion was calculated by applying unit-area rates estimated by MRC in the Hollow Tree ISA throughout other areas in the Coastal Belt and Yager geomorphic terrains, which were assumed to have similar skid trail densities as the Hollow Tree ISA. No skid trail erosion was assigned to Melange or Alluvial terrain areas (Section 3.5.5).
- In calculations of soil creep production using SEDMODL, different rates of creep were assumed to operate in the Coastal Belt and Yager areas (shallow creep of 0.001 m/yr and 0.002 m/yr for channels bordered by slopes with less than and greater than 30% gradients, respectively) and Melange areas (mantle creep of 0.01 m/yr) (Section 3.5.6).
- Inputs from earthflows, road surface erosion, road crossing and gully erosion, and soil creep were assumed to remain the same between the recent (1981–1996) and earlier (1966–1981) time periods, because we did not have any data with which to differentiate these processes between the two periods. This assumption is unrealistic for anthropogenic inputs from roads, given (1) temporal variations in

construction and maintenance practices (and regulatory requirements governing these practices), use levels, and densities, all of which cause variations in sediment inputs; and (2) the episodic nature of road crossing and gully erosion. Sediment inputs from earthflows also vary with climatic conditions.

- For converting volumes (e.g., m^3) to mass (tons), a bulk density of 1.4 t/m^3 was applied to sediment produced by road surface erosion and shallow soil creep, and a bulk density of 1.9 t/m^3 was applied to all other processes (Section 3.5.8).
- Coarse versus fine sediment fractions of sediment inputs were estimated for all sources, as follows: earthflows, shallow landslides, road crossing and gully erosion, and soil creep were assigned a 30% coarse and 70% fine fraction; skid trails were assigned a 10% coarse and 90% fine fraction, and road surface erosion was assumed to consist of 100% fine sediment (Section 3.5.8).

SEDIMENT SOURCE ANALYSIS RESULTS

The sediment source analysis results consist of four components: (1) summary of existing data on suspended sediment yield in the SFEB, (2) source analyses for ISAs, (3) extrapolation of these results basin-wide, and (4) summary of a sediment source analysis for the 1942–1965 period in the SFEB by USDA (1970).

Sediment Yield Data

Stillwater Sciences summarized data on suspended sediment yield for USGS stations in the SFEB, as reported in USACE (1980). These data provided a numeric constraint on sediment yield estimates and are summarized in Table ES-1 below and in Figure 1, which also presents data from other gaging stations in the SFEB. Total sediment yield estimates were based on the assumption that bedload is 15% of total load (after Sheppard 1963, Madej 1984). The bedload fraction of total load can be highly variable; studies from the Bull Creek basin have suggested possible bedload fractions ranging from 3% (LaVen 1987a) to 50% (Short 1993). Estimates of suspended sediment yield reported in Table ES-1 may underestimate actual yield; Ferguson (1986) found that traditional suspended sediment sampling techniques (as were used in developing the results in Table ES-1) may underestimate the actual suspended sediment load by up to 50% by failing to adequately account for the effects of high flows.

Only one USGS gaging station in the SFEB, South Fork Eel at Branscomb, includes the 1964 flood in its period of record. Data from elsewhere in the Eel River basin provide insight into the contribution of the 1964 flood event to average sediment yield over longer periods. Brown and Ritter (1971, as cited in Lisle 1990) indicate that at the Eel River at Scotia station, about 20% more suspended sediment yield occurred in three days during the December 1964 event than had occurred in the preceding 8 years. Kelsey (1980) estimates that in the Van Duzen River basin, the 1964 storm caused about 50% more sediment delivery during the 1941–1975 period than would have occurred during this period without the 1964 storm.

Table ES-1. Summary of suspended sediment yield data for gaging stations in the South Fork Eel basin.

Station	Drainage Area	Period of Record	Suspended Sediment Yield (t/yr)	Unit-Area Suspended Yield (t/km^2/yr)	Unit-Area Total Yield (t/km^2/yr)
South Fork Eel at Miranda	1390 km^2 (537 mi^2)	1958–1962	1,774,000	1276	1467
		1941–1965[1]	2,080,000	1496	1720
South Fork Eel at Branscomb	114 km^2 (43.9 mi^2)	1958–1970	108,700	954	1097
		1958–1962	89,200	783	900
		1941–1965[1]	77,000	676	777
Bull Creek at Weott	73 km^2 (28 mi^2)	1976–1979	220,170	3026	3480
Elder Creek	17 km^2 (6.5 mi^2)	1974–1975	11,300	671	772

1 Results for 1941–1965 are based on extrapolation from period of record over 1941–1965 period using sediment to discharge rating curves and are reported in USDA (1970).

Sediment Source Assessments for Intensive Study Areas

One component of our analysis was to conduct sediment source assessments in intensive study areas (ISAs) that were selected to represent different geomorphic terrains in the SFEB. The areas selected were Hollow Tree Creek and adjacent areas (collectively referred to here as the Hollow Tree ISA), Tom Long Creek, Sproul Creek, and Bull Creek. The results of sediment source analyses for these ISAs are presented in Tables ES-2, ES-3, and ES-4 and shown in Figures 4 and 5.

Results of the analysis indicated that in all ISAs, the overall unit-area sediment input in the earlier period was higher than in the recent period (Fig. 4), likely reflecting changes in climatic conditions and/or land uses. Overall, the difference between periods may have been even greater than indicated by the results of this study. The difference between periods was especially large in the Tom Long Creek ISA. In both periods, total sediment loading in the Tom Long Creek ISA was higher and the anthropogenic contribution was lower than in the Hollow Tree and Sproul Creek ISAs. This primarily reflects the effects of natural sediment production from earthflow toes and associated gullies in the Tom Long ISA, which is partly underlain by Melange terrain. Although we did not develop comparable results for the Bull Creek basin, results of previous studies (e.g., Fiori et al. 1999) and short-term suspended sediment yield measurements in Bull Creek indicate that unit-area sediment production in the Bull Creek basin is higher than in the other ISAs. In both periods, the unit-area sediment delivery was found to be lowest in the Sproul Creek basin compared to other ISAs (Fig. 4), a difference that is likely attributable to the absence of active earthflows in the Sproul Creek basin, topographic differences, and possibly differences in land use practices.

Table ES-2. Summary of sediment source analysis results.

Intensive Study Area	Sediment Loading ($t/km^2/yr$)		Anthropogenic:Total Sediment Input Ratio	
	Recent Period	1966–1981	Recent Period	1966–1981
Sproul Creek	552	866	0.76	0.51
Tom Long Creek	1,245	3,295	0.29	0.27
Hollow Tree Creek	693	918	0.57	0.62
South Fork Eel Basin	704	N/A	0.46	N/A

In both the Hollow Tree and Tom Long Creek ISAs, the ratio of anthropogenic to total sediment loading was about the same in both periods (Table ES-2, Fig. 5). In the Sproul Creek ISA, the ratio of anthropogenic to total inputs was higher in the recent period (0.76) than in the 1966–1981 period (0.51) (Fig. 5). This result may reflect the increase in timber harvest activities that occurred in the 1981–1994 period compared to the 1966–1981 period and reduced natural sediment production during this period of drier climatic conditions. The high anthropogenic contribution in the recent period in Sproul Creek is largely a function of the large amount of sediment production attributed to road crossing and gully erosion and therefore may be overestimated due to the high level of uncertainty associated with these estimates. Ratios of anthropogenic to total loading were not calculated for the Bull Creek ISA, although Fiori et al. (1999) indicated that a large percentage of the landsliding they documented was road-related.

Comparison of results of landslide assessments for the 1966–1981 (1966–1978 in the Hollow Tree ISA) and “current” periods for the selected ISAs indicated a number of patterns. Inner gorge landsliding, including natural and road-related features, was substantially higher in the earlier period than in the recent period in all ISAs, including three-fold higher in Sproul Creek and four-fold higher in the Hollow Tree ISA. (Differences were even greater in the Tom Long Creek ISA, but we had less confidence in the results because the estimates based on CDMG mapping for 1966–1981 appeared anomalously high.) In contrast, rates of non-inner-gorge landsliding (i.e., streamside natural, non-inner-gorge road-related, upland management) were similar between periods in the Sproul Creek and Hollow Tree ISAs, with a slight reduction in Sproul Creek and a slight increase in the Hollow Tree ISA between the previous and current periods. The influence of land use practices and regulations on these results is uncertain, but the results suggest that wetter conditions (characteristic of the 1960s and 1970s) have a greater influence on landsliding in inner gorge areas, whereas non-inner-gorge features may be less sensitive to climatic variation. This conclusion was based on limited data and would need to be tested with additional mapping, field validation, and assessment of frequency of landslide-triggering storm events for different time periods. Changes in timber harvest practices following passage of the 1974 Forest Practices Act, which created increased protections for streamside areas and increased use of cable yarding on steep slopes, may

have also contributed to changes in landsliding rates between the periods assessed here.

Table ES-3. Summary of sediment source analysis results for landsape unit-area sediment inputs (total annual input divided by ISA area) from each source category in each ISA per time period.

SEDIMENT SOURCE	INTENSIVE STUDY AREA AND TIME PERIOD					
	Sproul Creek		Tom Long Creek		Hollow Tree Creek	
	1981–1994	1966–1981	1981–1996	1966–1981	1978–1996	1966–1978
Earthflow toes and associated gullies	0	0	812	812	225	225
Inner gorge mass wasting, natural	81	287	0	641	12	96
Streamside (non-inner-gorge) mass wasting	44	129	32	903	54	23
Road-related mass wasting	37	18	35	29	112	186
Upland mass wasting	67	18	32	504	55	66
Road surface erosion	35	35	63	63	37	37
Road crossing mass wasting and gullying	264	264	219	219	176	176
Skid trail erosion	16	106	13	85	15	102
Soil creep	8	8	39	39	7	7
Total	**552**	**866**	**1245**	**3295**	**693**	**918**

Table ES-4. Summary of sediment source analysis results for relative contribution (fraction of total) of each source category in each ISA per time period.

SEDIMENT SOURCE	INTENSIVE STUDY AREA AND TIME PERIOD					
	Sproul Creek		Tom Long Creek		Hollow Tree Creek	
	1981–1994	1966–1981	1981–1996	1966–1981	1978–1996	1966–1978
Earthflow toes and associated gullies	0.00	0.00	0.65	0.25	0.33	0.25
Inner gorge mass wasting, natural	0.15	0.33	0.00	0.19	0.02	0.10
Streamside (non-inner-gorge) mass wasting	0.08	0.15	0.03	0.27	0.08	0.03
Road-related mass wasting	0.07	0.02	0.03	0.01	0.16	0.20
Upland mass wasting	0.12	0.02	0.03	0.15	0.08	0.07
Road surface erosion	0.06	0.04	0.05	0.02	0.05	0.04
Road crossing mass wasting and gullying	0.48	0.31	0.18	0.07	0.25	0.19
Skid trail erosion	0.03	0.12	0.01	0.03	0.02	0.11
Soil creep	0.01	0.01	0.03	0.01	0.01	0.01
Total	1.00	1.00	1.00	1.00	1.00	1.00

Our analysis suggested several other differences in sediment delivery patterns between the recent and previous periods. Because sediment production from shallow landsliding (an episodic process) was lower in the recent period, chronic inputs from earthflows (in ISAs where active earthflows were mapped), as well as road crossing and gully erosion, contributed greater fractions of overall loading in the recent period than in the previous period. Road surface erosion rates, although assumed to be the same between periods, were actually probably higher during the previous period, given more intensive logging activities (with its associated higher levels of road use) and less stringent road maintenance and construction practices during the earlier period (no data were available on changes in road density with time in the ISAs). Some of the differences observed in comparisons between periods are attributable at least in part to the methods and assumptions used in our analysis. Road crossing and gully erosion is likely driven at least in part by episodic processes (e.g., large storm events), although our analysis assigned the same rates for this category to both time periods because we did not have data with which to assess this source for the 1966–1981 period. Earthflow sediment production is also likely episodic, as evidence suggests that earthflows are more active and move more rapidly after a series of wet years or in response to a large event such as the 1964 flood (e.g., Kelsey 1980). Our assumption of constant production from earthflows is an attempt to estimate an average flux over time from what is a discontinuous (episodic) process.

1942 1965 Sediment Source Analysis

Stillwater Sciences summarized results of a USDA (1970) report to provide sediment production estimates for the entire SFEB for the period from approximately 1942 to 1965. The USDA (1970) report assessed erosional processes in the Eel and Mad River basins, including the SFEB, providing information on sediment yields in the 1940s to 1960s. The 1970 USDA study estimated sediment yields for the following four categories: (1) sheet and gully erosion; (2) streambank erosion; (3) landslides; and (4) roads. These categories and their definitions differed from those used by Stillwater Sciences for the current conditions sediment source analysis; results were therefore not strictly comparable. The 1970 USDA report found that the sheet and gully erosion category accounted for 12% of total erosion in the SFEB (126 $m^3/km^2/yr$), streambank erosion accounted for 47% (494 $m^3/km^{2/}yr$), landslides accounted for 41% (429 $m^3/km^2/yr$), and roads accounted for 1% (10 $m^3/km^2/yr$). Total sediment yield was estimated to be 1,060 $m^3/km^{2/}yr$ in the SFEB, or about 1,950 $t/km^2/yr$ assuming a bulk density of 1.9 t/m^3 for streambank erosion, landslides, and roads and 1.4 t/m^3 for sheet and gully erosion.

Results of Extrapolation to the SFEB as a Whole

For the current conditions period (1981–1996), Stillwater Sciences extrapolated the results of sediment source assessments for the ISAs to the entire SFEB based on GIS/DTM methods in order to develop SFEB-wide estimates of sediment loading and estimates of the anthropogenic:total ratio of this loading. Our analysis concluded that average sediment delivery in the SFEB from 1981–1996 was about 704 $t/km^2/yr$, with a ratio of anthropogenic to total loading of 0.46. The unit-area sediment delivery rate, which was based on extrapolation of results from the Hollow Tree, Tom Long, and Sproul creek ISAs, may be most representative of the SFEB upstream of its confluence with Bull Creek. This is because Bull Creek, which is not accounted for in the SFEB-wide estimates, appears to have substantially higher unit-area sediment yield than the rest of the SFEB. Considerable spatial variability in sediment loading is likely to exist in the SFEB, with the highest loading occurring in inner gorges along the mainstem, in the Bull Creek basin, and in areas underlain by Melange terrain. Reducing sediment loading in the SFEB to a

single number (about 700 $t/km^2/yr$) is therefore not particularly meaningful, as it does not reflect the substantial spatial variability in sediment fluxes.

Although we did not assess SFEB-wide loading for the 1966–1981 period, the differences between that period and the more recent period for the ISAs, as well as limited suspended sediment yield data from the SFE near Miranda gaging station (Table ES-1), suggested that sediment yield during this period was likely in the range of 1,000–1,500 t/km^2/yr (i.e., nearly double the amount estimated for the 1981–1996 period). The sediment yield estimated for the SFEB from 1942–1966 by USDA (1970)—1,950 t/km^2/yr—was almost three times higher than our estimate for the 1981–1996 period. Average annual runoff was about 10% higher in this period than in the more recent period, which may have accounted for part of this difference. The period assessed by USDA (1970) included the 1964 flood, which triggered substantial mass wasting and likely accounted for a large proportion of the sediment yield during this period (e.g., Lisle 1990). The 1942–1965 period was also characterized by intensive logging practices, particularly following World War II. Despite the occurrence of the 1964 flood, average annual runoff during this period was about the same as in the 1981–1996, according to analysis of discharge records from the SFE at Miranda gaging station. The USDA (1970) analysis used different methods than applied by Stillwater Sciences for the two more recent periods and incorporated substantially more field and aerial photograph data.

DISCUSSION/CONCLUSION

As noted above, our analysis concluded that average sediment delivery in the SFEB from 1981–1996 was about 704 t/km^2/yr, with a ratio of anthropogenic:total loading of 0.46. Given the uncertainties in our analysis, it is reasonable to round these values to 700 t/km^2/yr and 0.5. These data suggest that under current conditions and current land uses, there is a significant anthropogenic contribution to total sediment loading. Multiplying the sediment loading estimated for the current period (700 t/km^2/yr) by the natural fraction of this loading (0.5) suggests that in the absence of land uses, sediment loading in the SFEB would have been about 350 t/km^2/yr during the 1981–1996 time period. This number is very low for a basin with the topographic, climatic, and tectonic characteristics of the SFEB, which has been reported to have one of the highest sediment yields in the United States (e.g., Brown and Ritter 1971, Cleveland 1977). This suggests that our sediment source assessment may have substantially underestimated total sediment inputs, perhaps due to the omission of sources such as alluvial bank and terrace erosion. In general, this sediment source analysis for the SFEB contains considerable uncertainty, given the many assumptions, the limited time available to conduct field surveys, and the necessary focus on a subset of the basin (i.e., the ISAs). These constraints reduced our ability to differentiate between effects of various land management practices on geomorphic processes in the ISAs.

These results were compared to those of other sediment source analyses conducted in the region. In the South Fork Trinity River basin, Raines (1998) estimated average sediment delivery of 370 t/km^2/yr (1,053 t/mi^2/yr) from 1944 to 1990, with a ratio of anthropogenic to total loading of 0.28. For the 1975–1990 period, Raines indicated loading of about 180 t/km^2/yr (503 t/mi^2/yr) and a ratio of about 0.4. In the Redwood Creek basin, average sediment delivery of 1,720 t/km^2/yr (4,900 t/mi^2/yr) from 1954 to 1980 was estimated based on extensive research conducted in that basin (Redwood National and State Parks 1997). Although no ratio was identified, the Redwood Creek results indicated that 60% of total loading was "controllable." If these inputs are assumed to represent the anthropogenic contribution, this suggests a ratio
of 0.6 for the Redwood Creek basin. In the Garcia River basin, the following ratios of anthropogenic to total loading were estimated for various time periods: 0.70 in 1956–1965, 0.65 in 1965–1978, and 0.58 in 1978–1996 (M. O'Connor, pers. comm., 1999). Average overall loading estimated for the Garcia River basin from 1956 to 1996 was about 420 t/km^2/yr (1,200 t/mi^2/yr).

Although our sediment source assessment for the SFEB used different methods and time periods than the analyses of other river basins described above, all of these analyses indicate that the anthropogenic contribution to overall loading has been approximately 0.3 to 0.6 of the total in recent decades. The anthropogenic ratio we estimate for current conditions in the SFEB, about 0.5, is within this range. While these numbers (total loading and/or ratios) may not actually be significantly different from each other, it is reasonable to conclude that in recent times sediment contributions due to landuse accounts for about 30 to 60% of the total sediment loads in the SFEB and other northern coastal California rivers.

Our results indicate total unit-area loading (700 t/km^2/yr) from 1981–1996 that is nearly twice that of the South Fork Trinity River basin from 1944 to 1990 and nearly 4 times as large as loading from 1975 to 1990 (Raines 1998). The total loading in the SFEB during the current period has been less than that from Redwood Creek (1,720 t/km^2/yr) for the 1954 to 1980 period, although the SFEB results for 1942–1965 (1,950 t/km^2/yr; USDA 1970) and our rough estimate of loading from 1966 to 1981 (1,000 to 1,500 t/km^2/yr) in the SFEB are similar to the Redwood Creek results.

The main findings of our analysis are summarized as follows:

- For the most recent period evaluated in this sediment source analysis (1981–1996), the overall unit-area sediment input for the SFEB was about 700 t/km^2/yr, with about half of this sediment attributable to anthropogenic activities.
- In the 1942–1965 period, average sediment loading in the SFEB was about 1950 t/km^2/yr, according to a sediment source assessment conducted by USDA (1970), or about three times the loading assessed in the current period. The anthropogenic contribution during this period is unknown, but interpretation of the USDA (1970) results suggests a possible range of 0.14 to 0.37 for the anthropogenic:total loading ratio.
- The anthropogenic:total ratio estimated for the current period in the SFEB is within the range suggested in other river basins of about 0.3–0.6.
- The largest natural sources of sediment are earthflows and inner gorge landslides, whereas the largest anthropogenic sources are road-related landslides and road crossing and gully erosion.
- Sediment loading in the SFEB shows substantial spatial variability, with the highest loading occurring (1) in the northern portion of the basin (e.g., the Bull Creek basin), which has high precipitation and uplift rates, (2) in areas in the Melange terrain, where earthflows are a substantial sediment source, and (3) in inner gorge areas, where shallow landslides contribute to high sediment loading.

1. INTRODUCTION

The South Fork Eel River has been listed as an impaired waterbody because beneficial uses, including salmonid habitat, have been adversely impacted by high sediment loading and elevated temperatures (NCRWQCB 1996). To assist the U.S. Environmental Protection Agency with TMDL development for the South Fork Eel Basin (SFEB), Stillwater Sciences, under contract to Tetra Tech, completed a sediment source analysis for the basin. The results of this analysis are presented below, including identification of sediment sources and estimates of historical and current loading from various sediment source categories in the SFEB.

The size of the basin (1,783 km^2 [690 mi^2]), its complexity in terms of physical and biological conditions and land use history, access limitations (about 80% of the basin is in private ownership), a limited time frame, and budget constraints created substantial technical and logistical challenges to development of a sediment source analysis. We adopted an approach to sediment source analysis that accounted for these obstacles and constraints and was based on the following steps: (1) stratification of the watershed into geomorphic terrains (i.e., areas expected to have similar sediment production characteristics under reference and disturbed conditions), (2) analysis of existing data on sediment sources, (3) use of local intensive analysis (field data collection, sequential aerial photograph analysis) to estimate sediment production in representative portions of the SFEB, and (4) extrapolation of results from local intensive analysis to the entire SFEB based on GIS/DTM (Geographic Information Systems/Digital Terrain Modeling) methods. This approach does not yield the same quality of data as would result from a full sediment budget based on detailed basin-wide surveys and field work. Rather, it identifies and characterizes sediment sources in the basin and estimates source loadings by extrapolating the results of hypothesis-based intensive analysis conducted for selected subbasins. While this methodology departs from traditional approaches to sediment source analysis, it was necessary for completing a sediment source analysis for the SFEB because of the specific challenges faced in this basin.

In addition to quantifying sediment sources according to discrete sediment production processes, we further characterize sediment sources as being of natural or anthropogenic origin and by proportion of fine (<2 mm) and coarse (>2 mm) sediment. Quantification of hillslope-channel linkages requires identification of indicators of sediment inputs to stream channels. We used a *sediment ratio approach* to assess the potential sediment impacts of land management activities. This approach is based on the use of a ratio to compare the volume of sediment delivered from *anthropogenic sources* to that from *natural sources*; resulting in a ratio for anthropogenic:total sediment loading. We hypothesize that there is some ratio of anthropogenic:total sediment loading below which ecosystem functions will not be seriously altered (i.e., below which healthy, functioning stream systems will occur), although further study is necessary to determine what that ratio is. In particular, there is a need to combine sediment budget techniques with limiting factors analysis of salmonid populations to estimate this ratio.

In past TMDLs, mitigation of sediment impacts has been discussed in the context of mean annual sediment load as a numeric target (e.g., as was done for the TMDL for the Garcia River, California). Problems with basing load allocations on mean annual sediment yield include the following: (1) annual sediment load is highly variable under natural conditions due to climatic effects; (2) monitoring sediment load can be costly and imprecise; (3) no information about the source of sediment are provided; (4) a long time series of
sampling is required to estimate accurately the mean or trends; (5) a mean annual sediment load target

may fail to provide desired levels of protection and restoration. Using a sediment ratio as a hillslope indicator, rather than mean annual sediment yield, has the following potential advantages: (1) a ratio is a numeric target that identifies anthropogenic contribution and is less dependent on climatic conditions (i.e., natural variability between wet and dry periods) than annual sediment load; (2) a ratio can be used to estimate the effects of chronic fine sediment production from roads during dry years; a mean annual sediment load approach would not capture such dry-year impacts; (3) a target ratio may be applicable in different watersheds with similar geology, hydrology, and lithology; and (4) a ratio may be more meaningful for a given year or period than an average total sediment load. The ratio approach does not directly address remobilization of stored sediment. Further study of sediment ratios is necessary to reduce uncertainties about, for example, how ratios of anthropogenic:total loading or coarse versus fine loading vary between dry and wet years.

Calculating separate ratios for coarse (>2 mm) and fine (<2 mm) sediment recognizes that these particle size classes have differing potential impacts and residence times in the stream channel. Coarse sediment inputs may be more important in wet years, when episodic mass wasting processes deliver large volumes of sediment to channels. In contrast, fine sediment inputs may be more important in dry years, when total sediment delivery may be relatively low but when fine sediment inputs from chronic sources such as road surface erosion can alter gravel quality and other aquatic habitat characteristics. Moreover, the effects of coarse sediment in stream channels tend to last much longer than those of fine sediment, which must be "sustained" by chronic sources in order to have ongoing effects on stream channels.

2. BACKGROUND/ PHYSIOGRAPHIC CONDITIONS

The SFEB is located in the northern California Coast Range and has a drainage area of 1783 km^2, with an elevation range of 30–1,370 m (100–4,500 ft) (USBLM et al. 1996). About 20% of the basin is publicly owned: 12% is state land (mostly Humboldt Redwoods State Park), 7% is USBLM land, and about 1% is part of the University of California Angelo Coast Range Reserve (USBLM et al. 1996). Precipitation generally increases from south to north in the basin and is higher on the west side of the watershed than on the east side, with the highest average precipitation (2,920 mm/yr [115 in/yr]) occurring in the Bull Creek headwaters (USBLM et al. 1996). Vegetation on the west side of the basin is dominated by redwood and Douglas-fir (and tanoak in second-growth forests), while the east side of the basin is mainly characterized by oak woodlands and grasslands with some conifers. Stream channels, selected towns, and areas selected for intensive analysis (as discussed below) in the SFEB are depicted on Map 1. Map 2 shows the SFEB within a regional context.

The SFEB is frequently cited as having among the highest erosion rates in North America (e.g., Cleveland 1977, James 1983, Lisle 1990). These high erosion rates are attributable to a combination of widespread tectonic deformation of the underlying rocks, rapid uplift rates, steep topography, high precipitation rates, and widespread anthropogenic disturbances, particularly in the decades following World War II (e.g., Lisle 1990). Major erosional processes include mass movement and gullying, both of which are accelerated by human disturbance (Lisle 1990, Nolan and Janda 1982). USBLM et al. (1996) noted that the main existing sediment sources in the SFEB include debris slides and deep-seated landslides (slump-earthflow complexes) in the Melange terrain.

The landscape of the SFEB is moderately dissected and is dominated by large, inactive deep-seated landslides; laser altimetry for a portion of the SFEB suggests that the extent of these features has previously (e.g., CDMG 1984) been underestimated (W. Dietrich, pers. comm., 1998). The SFEB lies across the structural grain of a pull-apart basin, following east-west to northwest-southeast trending shear zones and faults. Tectonic uplift rates are very high in the northern part of the SFEB, particularly in the Bull Creek basin. Holocene and Quaternary geologic history of the SFEB, including evidence of long-term erosional cycles and tectonic uplift dynamics, are discussed in more detail in LaVen (1987a). Seismicity may also influence mass wasting rates in parts of the SFEB, as discussed in James (1983) and Fiori et al. (1999). Lisle (1990) noted that because of continuing tectonic uplift, mainstem channels are typically incised more deeply than their tributaries, contributing to a high frequency of streamside landslides along high-order channels. Such landslides are major sources of sediment.

Hillslope processes and channel morphology in the SFEB have been greatly influenced by large storm and flood events. The 1964 flood accelerated sediment and organic debris delivery to streams, particularly in the lower and middle portions of the basin that have been undergoing a cycle of entrenchment during the late Holocene (USBLM et al. 1996). Aggradation and channel widening in reaches with substantial landsliding following the 1964 flood has likely triggered additional streamside landslides by undercutting and destabilizing the base of hillslopes (Kelsey 1977, Janda and Nolan 1979; as cited in Lisle 1990). The 1964 flood likely resulted in considerable storage of sediment delivered by mass wasting in the lower reaches of tributary channels, with remobilization and gradual delivery of that sediment to the mainstem South Fork Eel River in the following decades (USBLM et al. 1996, USBLM 1983).

Information on land use history in the SFEB is provided in the discussions of the intensive study areas (ISAs) (Section 4.2). USBLM et al. (1996) noted that many lands formerly used for logging and ranching have been subdivided, with widespread use of old logging roads for primary access, old skid trails as driveways, and landings as homesites, all of which contribute to chronic surface erosion and episodic road failures. Poor maintenance, design, and drainage on many of these roads exacerbate erosion problems.

2.1 Geology

The geology of the SFEB is dominated by the Franciscan Complex, which includes the Coastal Belt, Yager, and Central Belt (Melange) units. These geologic units were formed 38–80 million years ago during the Tertiary and Cretaceous periods. Deeply weathered rocks of the Franciscan Complex are highly unstable, largely because of the presence of many large and small faults and shear zones, and high precipitation rates. Valleys in portions of the SFEB are filled with Quaternary alluvium. Geologic units in the SFEB have been previously mapped by CDMG (1984) and James (1983) and are shown in Map 3. The characteristics of the dominant geologic units in the SFEB are described below.

Central Belt/Melange Matrix with blocks: The Central Belt geologic unit, also referred to here as "Melange Matrix with blocks," occupies about 20% of the SFEB, and is concentrated in the eastern portion of the watershed. The Central Belt unit is an assemblage of fragmented and sheared Franciscan Complex rocks and Mesozoic Era volcanic and metavolcanic rocks (Blake et al. 1985, Wahrhaftig and

Birman 1965). The unit consists of a pervasively sheared, clay-rich matrix of shale and greywacke, referred to here as Melange Matrix. Melange Matrix contains discontinuous blocks ranging in size from meters to kilometers of competent sandstone (Coastal Belt), chert, high-grade blueschist, serpentine and serpentinized ultramafic intrusive rocks (mainly dunite, peridotite, and gabbro), eclogite, greenstone, pillow basalt, diabase, and minor pyroclastic rocks. Many of the contacts between Central Belt and adjacent formations are tectonic and are characterized by pronounced deep-seated mass wasting.

Melange Matrix areas are characteristically naturally unstable and prone to mass wasting even on low-gradient slopes. Chronic sediment production from gullying and mass wasting on active earthflow toes characterizes this terrain (CDMG 1984, Kelsey 1978) and is likely the dominant sediment source under natural conditions in Melange-dominated watersheds. Kelsey (1978) indicates that earthflows occupy 10% of the Melange Matrix of the Central Belt, and limited mapping by Stillwater Sciences (for this report) indicates that *active* earthflows occupy 5% of Melange Matrix area in the SFEB. Although this comparison suggests that half of all earthflows are active, it is likely that dormant earthflows have been traditionally undermapped, as noted above, and that the proportion of earthflows that are active is relatively small. Most of the sediment delivered to channels in the Melange unit from earthflow toes and gullies is sand or finer material (Nolan and Janda 1995, Kelsey 1980). Mantle creep (i.e., deep creep) associated with Melange Matrix chronically delivers colluvium into stream channels in non-earthflow areas (e.g., USDA 1970). Discrete failures such as slump-earthflows landslides (some as large as several square kilometers), streambank erosion (in the form of bank slumps at toes of either earthflow-slumps or mantle creep) and surface erosion (sheet erosion, rilling, and gullying) are also naturally associated with Melange Matrix. The competent sandstone blocks within the Melange Matrix, where sufficiently large to display geomorphic processes distinct from surrounding Melange Matrix areas, are characterized by erosional processes described for the Coastal Belt, including shallow landsliding and relatively dormant deep-seated wedge (glide) mass wasting.

Melange Matrix is also characterized by moderate relief and moderate-to-gentle slopes. Melange Matrix areas typically support woodland, brush, and grassland vegetation, with recent historical and current land use consisting mainly of livestock grazing.

Coastal Belt: Rocks of the Coastal Belt Franciscan unit are typically folded and locally faulted, and consist of structurally deformed, massive, hard graywacke sandstone and shale interbedded with small amounts of limestone and pebble conglomerate (Blake et al. 1985, Wahrhaftig and Birman 1965). The bedrock is locally homoclinally folded, generally has a northwest strike, and dips moderately to steeply (30 to 85 degrees) to the northeast. Bedrock may be vertically oriented and highly disrupted near fault contacts. The graywacke sandstones are competent, generally resistant to weathering, and commonly fine- to medium-grained in texture, but may be coarser-grained in some areas and have a chloritic matrix. The conglomerates are composed of clasts of quartzite, graywacke, greenstone, and red, black, and green chert (this also characterizes the Yager unit, descibed below). The rocks of this unit (and of the Yager formation) were deposited in marine basins during the Upper Cretaceous to late Eocene.

In the Coastal Belt, hillslope erosion and sediment delivery to channels are dominated by shallow landslides (and associated debris flows), particularly in inner gorge areas (e.g., Kelsey 1980, Lisle 1990). Shallow debris slides are also common in colluvial hollows and in areas associated with thrust faults (Kelsey 1987). Large deep-seated wedge landslides (many of which are likely dormant) are another important mass wasting process in the Coastal Belt, particularly over a geologic time scale. The Coastal Belt unit is generally more deformed than the Yager formation (which is described below).

Topographically, this is the most dissected unit of all units in the SFEB, with high relief, steep slopes, and a high percentage of the landscape unstable and prone to shallow mass wasting. Vegetation is dominated by coniferous (redwood and Douglas-fir) forest in the Coastal Belt, and timber harvesting is the main land use.

Yager Formation: The Yager unit consists of homogenous competent siltstones and is sometimes lumped with the Coastal Belt because of their similarities. This unit occupies 16% of the SFEB, concentrated in the northern portion of the basin. Yager formation rocks are well-bedded and indurated, locally highly sheared and folded mudstone-rich turbidites (silt-shale) interbedded with sandstone and polymict conglomerate. Muscovite-bearing sandstones are quartzofeldspathic and arkosic. Silty shale and mudstone disaggregate by slaking when wetted. Topographically, slopes are relatively gentle. Mass wasting processes include deep-seated landsliding (now likely dormant), gully erosion, rotational slumping, earthflows, and debris slides. Seismic activity may have an important influence on mass wasting in Yager portions of the SFEB (e.g., Fiori et al. 1999).

Quaternary alluvium/Stream channel and terrace deposits: The Quaternary alluvium unit consists of alluvium deposited in tectonically subsiding basins in major northwest-trending fault zones within the Coast Ranges (Christensen 1966; Davis 1988), including the SFEB. This includes Holocene stream alluvium deposited in valley fills, river terraces, marine terraces, and landslides, and hillslope alluvial/colluvial fans. Extensive river terraces are present above the valley floors along high-order streams in the SFEB, formed by fluvial erosion in the Quaternary basin-fill (Ogle 1953). Valley bottoms in smaller drainages in the SFEB are extensively alluviated and sharply incised by streams, with multiple (up to 14 along the mainstem SFE [Bickner 1993]) flat river terraces of poorly consolidated interbedded gravel, sand, silt, and clay currently providing a source of sediment to streams. Bickner (1993) found that the oldest (strath) terrace along the SFE near Garberville, located at 310 m above the channel, was dated at 295 to 680 ky (thousand years old). The formation of and downcutting through these nonmarine alluvial valley fills might have been initiated by changes in climate and/or regional uplift in the late Holocene.

Other small geologic units are also present in the SFEB, including Leggett peridotite and Wildcat Group. The Wildcat Group geologic unit consists of Tertiary sedimentary deposits and occurs in the area of Garberville in the SFEB, although most Wildcat Group rock has been eroded away.

2.2 Topography and Shallow Landslide Hazard

A DTM-based shallow landslide slope stability model, SHALSTAB (see Dietrich et al. 1992, 1993 and Montgomery and Dietrich 1994 for details on theory and application of this model) was used to characterize the topography of the SFEB and to identify the shallow landslide hazard potential in the basin. This analysis provides information that is relevant to a TMDL and associated land management, because it offers insight into the concentration of high hazard areas in different parts of the watershed and into areas where land uses may be most likely to contribute to increased shallow landsliding. SHALSTAB is a predictive tool that characterizes the potential for shallow landsliding across the landscape, classifying the
landscape by landslide hazard categories. The model is derived from an assumption that shallow landsliding can be predicted from an infinite slope stability model that uses a steady state shallow subsurface flow model to estimate local pore pressure. The model predicts that the spatial pattern of potential shallow instability is governed by the surface topography (local hillslope gradient and local

drainage area per unit contour length).

Areas classified as “chronic” are where the slope is steeper than the maximum stable angle of the material (i.e., the internal angle of friction of the soil). Consequently, these areas have the highest potential for instability, as they can fail when dry. Areas with sufficiently low gradients will not fail even when saturated—such areas are classified as stable. The landscape between these two states is then classified according to potential instability using the hydrologic ratio of effective precipitation (q) and soil transmissivity (T). The logarithm of the ratio q/T provides a metric used to classify slopes into categories of potential instability, including low, medium, moderately high, and high instability classes. The only variables required to generate the log (q/T) values are hillslope gradient and area drained per unit contour width. The model has been tested and validated in northern California (Dietrich et al. 1998), Oregon, and Washington (Montgomery et al. 1998) and has been shown to successfully identify those parts of the landscape susceptible to shallow landslide hazards.

The SHALSTAB model was applied to the SFEB as a whole using 30-m digital-elevation data. SHALSTAB results for the the SFEB, based on 30-m DEMs (Digital Elevation Models), are summarized in Table 1 and are shown on Map 5. SHALSTAB results were also generated for selected portions of the basin (i.e., the intensive study areas, or ISAs) using 10-m DEM data, as discussed in Section 4.2 and Appendix A.

Table 1. Summary of SHALSTAB results for SFEB, 30-m grid.

Log q/T Value and Hazard Class	**Area (km^2)**	**% Total**
Chronic instability	1.37	0.1
<–3.1 (High)	67.2	3.8
–3.1 to –2.8 (Moderately High)	103.3	5.8
–2.8 to –2.5 (Moderate)	198.7	11.1
–2.5 to –2.2 (Moderately Low)	187.4	10.5
–2.2 to –1.9 (Low)	44.0	2.5
>–1.9 and Stable	1,180.9	66.2
TOTAL	1,782.9	100

The results shown in Table 1 likely overestimate the land area that is “Stable” because of the use of 30-m DEM data, which tends to homogenize and flatten the landscape compared to 10-m DEMs and actual topography (see Appendix A).

3. SEDIMENT SOURCE METHODOLOGY

The sediment source analysis combined analysis of existing work describing past and recent sediment yields (e.g., MRC 1999, USDA 1970) with quantification of sediment production in intensive study areas (ISAs) that were selected as part of the watershed stratification process. Results from ISAs were then extrapolated to the whole SFEB using the GIS/DTM. Where possible, we have drawn on existing data from the SFEB in assessing sediment sources. For each sediment source, magnitudes of sediment inputs from different source categories were estimated and a ratio of anthropogenic to total sediment production was calculated. The methods used in the sediment source analysis are discussed below, including discussion of key existing data sources, watershed stratification and selection of ISAs, time periods and sediment source categories that were assessed, and GIS/DTM methods.

3.1 Analysis of Existing Data

Many studies have previously been conducted in the SFEB and contributed to the development of sediment source analyses for the basin. Information from these sources was reviewed by Stillwater Sciences and is reported in relevant sections of this report. Some of the key sources of existing information include the following:

- A report by USDA (1970) that assessed watershed processes and sediment delivery in the Eel and Mad River basins, including the SFEB, providing information on sediment yields in the 1940s to 1960s. This document provides a quantitative, source-specific sediment source assessment for the SFEB for the 1942–1965 period that captures the 1964 storm and flood event.
- A “watershed erosion investigation” by California Department of Water Resources (James 1983) of the SFEB based on analysis of 1981 aerial photographs.
- CDMG geomorphic maps (1984) which were based on mapping of landslide features using 1981 aerial photographs. Stillwater Sciences obtained digital versions of these coverages for use in our assessment.
- Numerous studies from the Bull Creek basin, including a sediment source analysis for Preacher Gulch, a small tributary in the upper watershed (Fiori et al. 1999), and studies of sediment sources in Cuneo Creek (Short 1993). These studies formed the basis of our sediment source analysis for the Bull Creek basin.
- In-stream suspended sediment data. Data on suspended sediment yield have been obtained for USGS stations in the SFEB and were assessed to provide a numeric constraint on sediment yield estimates.
- Preliminary results of a Level II watershed analysis by Mendocino Redwood Company (MRC) in the Hollow Tree Creek basin (MRC 1999).
- Other existing data on roads and other sediment sources, including road erosion studies on U. S. Bureau of Land Management (BLM) lands in the basin (PWA 1997).

In addition, existing sources of GIS data were used extensively in the sediment source analysis, as discussed in Section 3.6.

3.2 Watershed Stratification

The sediment source analysis stratifies the SFEB to delineate areas expected to have similar geomorphic processes, response potential, and sediment yields. Existing data, geologic maps, and a 30-m DTM were used to stratify the watershed. Lithology was used as the primary stratification criterion, based on the hypothesis that lithology has a dominant influence on sediment production and that the relative importance of different sediment transfer processes varies between terrains. This hypothesis has been supported by findings elsewhere in the region (e.g., Janda 1979, as cited in Lisle 1990). An additional stratification criterion was topography and shallow landslide instability, as indicated by the 30-m DTM and the SHALSTAB model. Our analysis assumes that in each geomorphic terrain, soils, hydrology, vegetation, and thus hillslope and channel processes are similar. Vegetation and geology show substantial overlap in the SFEB; for example, the extent of Melange Matrix terrain corresponds closely to that of grasslands and oak woodlands in the SFEB.

This stratification divides the basin into four “geomorphic terrains” expected to have different sediment production characteristics and processes: (1) Melange terrain (Central Belt Franciscan), (2) Coastal Belt Franciscan terrain, (3) Yager terrain, and (4) “Alluvial terrain” (terraces and floodplain alluvium [i.e., stream channel and terrace deposits]). Geomorphic terrains are named after dominant geologic units, but they do not strictly follow geologic unit delineations. Areas were lumped together and geologic coverages were simplified to create geomorphic terrains based on primarily on lithology and secondarily on criteria such as geography (location in the SFEB), topography, precipitation, and seismic activity. For example, the area defined as “Yager terrain” contains small areas of Coastal Belt geology but is dominated by Yager formation geology, is located in the northernmost portion of the SFEB, and has the highest precipitation rates and levels of seismic activity in the SFEB (James 1983). The “Coastal Belt terrain” incorporates areas with Yager, Wildcat Group, and Leggett Peridotite geologic units, is concentrated in the western portion of the SFEB, and has generally consistent precipitation rates (James 1983) and topography. The Stillwater Sciences stratification of the SFEB into geomorphic terrains is shown on Map 4 and is summarized in Table 2.

Table 2. Area of geomorphic terrains in South Fork Eel basin delineated by Stillwater Sciences as part of watershed stratification (as shown on Map 4), including area within Yager and Coastal Belt terrains identified as innner gorge (IG) by Stillwater Sciences.

Geomorphic Terrain	Area (km^2)	% of Total
Yager Formation	289.7 (15.8 km^2 IG)	16
Melange (Melange Matrix plus Blocks in Melange)	350.5	20
Coastal Belt (includes some Yager and other lithologies)	1056.2 (96.7 km^2 IG)	59
Alluvial terrain (Valley Floor/Terraces and Modern Stream Deposits)	86.5	5
TOTAL	1782.9 (112.5 km^2 IG)	100

Predictions of shallow landslide hazard using the SHALSTAB model were used as a secondary stratification criteria. The SHALSTAB model suggests that areas in the Melange and Yager terrains have a higher proportion of area in the stable SHALSTAB class (i.e., slopes are relatively gentle in these areas) than areas in the Coastal Belt terrain, which are generally more dissected and steep. The percentage of land in the Stable category in these terrains is as follows: 58% in the Coastal Belt, 73% in Yager, and 79% in Melange (Map 5). Conversely, about 25% of land in the Coastal Belt has a log q/T value of less than −2.5 (i.e., is in the Moderate, Moderately High, High, or Chronic hazard classes), compared to about 20% of land in these classes in the Yager terrain and about 12% in the Melange terrain (Map 5).

In addition to stratifying the watershed into geomorphic terrains, we delineated large inner gorges, because these areas are a substantial sediment source with a sediment-input contribution disproportionate to their extent (e.g., USDA 1970). Inner gorges characterize the mainstem SFE, Hollow Tree Creek, Tenmile Creek, Rattlesnake Creek, Cedar Creek, and other higher-order channels, and mainly occur in the Coastal Belt geomorphic terrain. Some smaller basins also appear to have pronounced inner gorges characterized by streamside landsliding. Large inner gorges were delineated based on analysis of CDMG geomorphic maps, including inspection for evidence of chronic landsliding zones, breaks in slope at about 200-m distance from the channels, and inner gorge delineations. SHALSTAB maps (30-m grid in the SFEB, 10-m grid in ISAs) and channel Strahler order maps for the ISAs (see Section 3.3) were also consulted. The objective of this delineation was to capture large, undeniable inner-gorge features.

The total length of the large inner gorges identified by Stillwater Sciences is about 250 km, or 5% of the total channel length in the SFEB (assuming an average drainage density of 3 km/km^2 in the SFEB, as suggested by GIS channel networks in the ISAs); these features are shown on Map 4. The following average geometry was assumed for inner gorges: 30 degree slopes (Kelsey 1988), a 200-m sideslope length (Kelsey [1988] reported a 180–350 m range for the Redwood Creek basin), and a valley/channel width of 100 m within the inner gorges. This suggests an average width of inner gorge features of about 450 m ([200 m][cos30][2]+[100 m]). The extent of inner gorges as shown on Map 4 likely substantially underrepresents the true extent of inner gorges in the SFEB. This delineation suggested that most large gorges occur in 3rd-, 4th-, and 5th-order channels.

3.3 Intensive Analysis

Areas within each of the three major geomorphic terrains (Coastal Belt, Yager, and Melange) were selected for intensive analysis in which sediment sources were quantified. These analyses were designed to gather data on mechanistic relationships describing sediment production dynamics in areas representative of the SFEB. Adoption of this approach and selection of ISAs was driven by the complexities, size, and access limitations that characterize the SFEB. Data collected in our ISAs were used as a basis for extrapolating sediment production estimates across the SFEB using DTM-based information on general attributes for the broader watershed (e.g., slope, road density, log q/T). Areas where intensive analyses were conducted were among the few areas to which we had access. These areas included:

- Hollow Tree Creek basin and adjacent areas in MRC ownership, collectively referred to here as the Hollow Tree ISA (representative of the Coastal Belt terrain and of industrial forestry land use);
- Sproul Creek basin (representative of Coastal Belt and Yager areas with recent timber harvest activity)

- Tom Long Creek basin (representative of areas in the Melange and Coastal Belt terrains and of mixed land uses including dispersed residential, grazing, and non-industrial timber harvesting)
- Bull Creek basin (representative of Yager terrain; high precipitation, uplift rates and seismic activity; and of a land use pattern characterized by substantial impacts followed by a “recovery” period).

More detailed descriptions of each ISA are included below with the sediment source assessments for these areas. The location of these areas in the SFEB is shown on Maps 1 and 4, and Maps 6–9 show additional detail for each ISA. Intensive analysis was not carried out for Alluvial terrain, although existing studies related to alluvial areas in the Bull Creek basin are discussed (e.g., LaVen 1987a, b).

Methods used for the sediment source analyses differed between ISAs, given varying amounts of pre-existing data. For the Hollow Tree Creek basin, preliminary results of a sediment source assessment by Mendocino Redwood Company (MRC) as part of a Level II Watershed Analysis (based largely on Washington DNR methods [WFPB 1997]) were available. That effort included mapping of landslides and skid trails from 1978 and 1996 aerial photographs and field validation in June 1999. For the sediment source analysis in the Sproul and Tom Long basins, Stillwater Sciences completed aerial photograph analysis. The sediment source assessment for the Bull Creek basin relied primarily on analysis of existing studies; no additional mapping was carried out for the Bull Creek basin by Stillwater Sciences. In addition, GIS/DTM methods, limited field surveys, and assumptions based on regional literature were applied in developing sediment source assessments in the ISAs. Additional detail on these methods is provided below.

3.4 Time Periods Used in the Sediment Source Analysis

The sediment source analysis presented here assessed three time periods: 1942–1965 (for the whole SFEB), 1966–1981 (for ISAs only), and 1981–1996 (for ISAs and the whole SFEB), with some variations in the length of time periods because of differences in source data. Our analysis largely focused on determining the magnitude of sediment sources and the ratio of anthropogenic to total inputs under current conditions, approximated by the 1981–1996 period. This approach places lesser emphasis on determining sediment inputs during previous time periods than in many time-sequence sediment budgets, in part because of the availability of the USDA (1970) report detailing sediment sources in the SFEB from 1942 to 1965. Emphasizing current rather than historical sediment loading is appropriate given the TMDL context of identifying and reducing current sediment sources, including ongoing legacy effects of previous land use practices on current sediment production. Sediment sources during previous time periods were evaluated to the extent possible using available data, as described below. Focusing our analysis on the current time period and relying on existing data for previous time periods results in the different methods being used for different time periods, therefore limiting the ability to fully determine trends in sediment production. The storm history associated with these time periods is discussed in Section 4.1 below.

3.4.1 Methods for Current Conditions Time Period

Assessment of sediment sources under current conditions relied on a combination of field surveys, mapping using 1994 and 1996 aerial photographs, and analysis of existing data. The lengths of the time periods assumed to represent “current conditions” in various ISAs were not equal in all cases because of differences in methods and aerial photograph sources. Therefore, the current conditions assessments in the

Hollow Tree, Tom Long, and Sproul Creek ISAs are assumed to apply to the 1978–1996, 1981–1996, and 1981–1994 periods in each of these ISAs, respectively. As described above, the sediment source assessment for the Hollow Tree ISA relied heavily on preliminary results of a Level II watershed analysis by MRC (for the Hollow Tree ISA) using 1996 aerial-photograph mapping (and 1978 photographs for the earlier period, resulting in the assumption of a 1978–1996 time period for this ISA). Stillwater Sciences carried out aerial photograph mapping of erosional features for the Tom Long and Sproul Creek basins using 1996 (1:24,000) and 1994 (1:12,000) photographs, respectively; classification and quantification of mapped erosional features is discussed in Sections 3.5.1 and 3.5.2.

Reliance on 1994 and 1996 photographs failed to capture the January 1, 1997 storm, which produced widespread mass wasting in portions of the SFEB (e.g., Fiori et al. 1999). Stillwater Sciences and EPA obtained 1998 aerial photographs of the SFEB in an effort to capture the effects of the January 1, 1997 storm and the 1997–1998 El Niño winter. The 1998 photographs are at a 1:40,000 scale, however, and their resolution was insufficient for mapping smaller landslides. The 1998 photographs were therefore used for qualitative purposes only. If the "current conditions" sediment source assessments had incorporated landslide data from the 1996-1997 and 1997-1998 winters, resulting estimates of sediment flux would likely have been higher (estimates of road crossing and gully erosion, because they were based on 1999 field surveys, do incorporate the effects of these wet winters).

Aerial photograph mapping consisted of mapping of shallow landslides and active deep-seated slides (toes only) using mylars and topographic/SHALSTAB maps. Additional detail on mapping methods is provided in Sections 3.5.1 and 3.5.2 below.

3.4.2 Methods for 1966–1981 Time Period

Stillwater Sciences did not collect new data on sediment sources during the 1966–1981 period, instead relying on analysis of existing sources. Sediment source analysis for the 1966–1981 time period relied primarily on CDMG maps for estimating landsliding inputs and on the assumption that sediment delivery from chronic processes was the same as under current conditions (1981–1996). During this period, intensive timber harvesting occurred in parts of the SFEB and annual runoff was highly variable, with both very wet years (e.g., 1974) and very dry years (e.g., 1977) (Figure 2). Overall, the 1966–1981 period was wetter than the more recent period in the SFEB; analysis of USGS records from the SFE at Miranda gauge (Figure 2) indicated that average annual runoff was higher in the 1966–1981 period than in the 1981–1996 period. In addition, regulations governing timber harvesting and associated road construction activities became more stringent with passage of the Forest Practices Act in 1974.

The California Division of Mines and Geology (CDMG) completed geomorphic mapping of nearly the entire SFEB based on 1981 aerial photographs. Assuming that aerial photographs represent an approximately 15-year period of record (most landslides revegetate within this time), results of this mapping served as a basis for assessing sediment production from landsliding for the period from 1966 to 1981. The CDMG maps were made available in digital form in 1999 (with some updates from the paper maps published in 1984) and were acquired by Stillwater Sciences to facilitate GIS/DTM analysis of the CDMG data. Geomorphic features mapped by CDMG are shown on Maps 11 and 12, which are based on the digital version of the CDMG maps.

Landslide sediment production for 1966–1981 was estimated based on mapping of active landslide features by CDMG. In addition, Stillwater Sciences used features mapped by CDMG as earthflows to estimate the length of earthflow toes along stream banks (earthflow toe banks). Methods used in analysis of CDMG landslide data are discussed in Section 3.5.1 (Shallow Landslides) and 3.5.2 (Earthflows and Associated Gullies). Stillwater Sciences did not evaluate dormant deep-seated landslides and dormant debris slide features mapped by CDMG, as these were assumed to produce no sediment during the 1966–1981 period. For skid trails, unit-area rates of sediment delivery estimated by MRC for the 1966–1978 period in the Hollow Tree ISA were applied to other ISAs (see Section 3.5.5 [Skid Trail Erosion] for additional discussion of this calculation). For other processes (earthflows, soil creep, road crossing and gully erosion, and road surface erosion), sediment delivery was assumed to be the same as in the recent drier 1981–1996 period (methods of calculating sediment production for these sources are described in Section 3.5). For analysis of the Hollow Tree ISA, we also used preliminary results of landslide mapping using 1978 aerial photographs by MRC (results for the Hollow Tree ISA are therefore assumed to apply to 1966–1978).

Assuming that CDMG mapping represents a 15-year period (1966–1981) provides continuity with the time period assessed in the USDA (1970) report discussed below, which extends to 1965. Some features mapped by CDMG from 1981 photographs may have been caused by the December 1964 storm and flood event.

3.4.3 Methods for 1942–1965 Time Period

A report by USDA (1970) includes a sediment source analysis of the SFEB for the 1942–1965 period, based on extensive aerial photograph interpretation and field surveys. Stillwater Sciences did not conduct new analysis of sediment sources in the SFEB during this period. Rather, we relied on the the USDA (1970) report for description of sediment sources from 1942 to 1965 and for comparison with more recent periods. The results of this report, which reports sediment yield by source category and identifies anthropogenic contributions, are summarized in Section 4.3 below to provide insight into erosional processes from 1942 to 1965—a period in which extensive timber harvesting and two large floods (1955 and 1964) occurred.

In addition, Stillwater Sciences analyzed various other aerial photographs of portions of the basin, including photographs from 1941–1942 (which precedes industrial timber harvesting and represent reference conditions and a dry period), 1976, and 1998.

3.5 Sediment Source Categories

Sediment sources were quantified according to the following source categories: shallow landslides, deep-seated landslides, soil creep, road surface erosion, road crossing and gullying erosion, and skid trails. Selection of these source categories was based on literature review, field visits, aerial photograph assessment, and experience in northern coastal California. Sediment production from these source categories was assessed in intensive study areas, and the results were extrapolated to the SFEB as a whole. A number of other possible categories, such as bank erosion and hillslope (non-road-related) surface erosion, were not quantified (see Section 3.5.7 for further discussion). Details on the methods used for estimating sediment production from the categories that we quantified are discussed below.

3.5.1 Shallow Landslides

Shallow landslides (including debris slides and debris torrents) were identified on aerial photographs and using CDMG geomorphic maps in ISAs, as described above. This included estimates of causality and delineation of inner gorge failures. Results of shallow landslide mapping from other studies (e.g., MRC 1999, Fiori et al. 1999) were also used.

Aerial photograph mapping of shallow landslides by Stillwater Sciences

For shallow landslides, only scars were mapped (debris-fan deposits were not mapped). The size of mapped landslide features was measured to determine surface area, and mapped features were digitized. Existing studies were consulted to estimate average shallow landslide depths. Literature data suggest average depths of 0.5–2 m (Kelsey et al. 1995, Redwood Creek basin) and 1.2–1.5 m (Kelsey 1977, Van Duzen River basin). Stillwater Sciences assumed an average depth of 1.3 m for estimating landslide volumes. For debris torrents (also sometimes referred to as debris flows or avalanches), scars and tracks were mapped. For estimating delivery from these features, the mapped length of each torrent track was assigned a volume of 8 m^3 per meter of track, a value based on Benda and Cundy (1990) that was also applied by Raines (1998) for the South Fork Trinity River basin. The resulting volumes for runouts (torrent tracks) were added to mapped scar volumes. Benda and Cundy's (1990) data on average torrent-track volumes from studies in Oregon were applied because no local data on average volumes of debris torrent tracks were available, although we acknowledge that this likely introduces some errort into estimates of debris torrent volumes.

Landslide age and sediment delivery ratios (the proportion of sediment mobilized on hillslopes by shallow landslides that reaches the channel) were estimated as well. As part of the mapping process and to assist in determination of landslide ages, we consulted existing landslide maps (CDMG 1984, James 1983) and additional aerial photographs (or copies of photographs) (e.g., 1998, 1966) for the ISAs.

For each landslide feature, the land-type association was identified using the following categories: (1) inner gorge (based on Stillwater Sciences' delineation of large inner gorge features, as described in Section 3.2), (2) non-inner-gorge streamside (those occurring in non-inner-gorge areas along second-order and larger channels, typically along streams in V-shaped valleys), and (3) upland (originating greater than 40 m from a stream, and/or in first-order basins, which typically do not have V-shaped valley topography conducive to streamside landsliding).

Stillwater Sciences estimated the relative proportion of natural versus anthropogenic landslides using the following criteria: (1) landslides associated with roads were identified as anthropogenic, (2) all non-road-related inner gorge slides were assumed to be natural, (3) all non-inner-gorge streamside slides were assumed to be natural if no road or timber harvest associations were visible, (4) all upland slides were assumed to be anthropogenic. These basic assumptions were applied to assist development of ratios of anthropogenic:total loading. We acknowledge that some upland slides are natural, while some inner gorge and non-inner-gorge streamside landslides (particularly point slides) are likely anthropogenic. The assumption that large inner gorge landslides are natural was supported by inspection of 1942 (pre-logging) aerial photographs of selected inner gorge areas (SFE from Angelo Reserve to Rattlesnake Creek; mainstem Hollow Tree Creek) by Stillwater Sciences, which indicated the presence of many large landslides along inner gorges, including some that were mapped as “active” by CDMG from the 1981 aerial photographs. Non-road related inner gorge and streamside slides we observed were in forested areas that had not been recently harvested, although all such areas had likely been historically harvested and legacy effects of previous harvest activities may have contributed to the landslides, particularly point slides, in these areas. In addition, effects of anthropogenically influenced aggradation on triggering inner gorge and other streamside failures are difficult or impossible to quantify from aerial photography. The majority of upland slides we observed on aerial photographs appeared to be associated with some type of timber harvest activity.

We hypothesize that the errors in these assumptions (overestimating the anthropogenic contribution to upland landsliding and underestimating anthropogenic contributions to inner gorge and other streamside failures) may counterbalance each other and result in reasonable overall estimates of the ratio of anthropogenic:total loading. We developed a sensitivity analysis evaluating the effects of our assumptions about landslide causality (outlined above) on the overall anthropogenic:total ratios calculated for all sediment sources in ISAs (this is presented in Section 4.2.5 below [Discussion of Intensive Analysis Results]).

In some cases, complete aerial photograph coverage and mapping were not available for the ISAs. In the Hollow Tree basin, only areas in Mendocino Redwood Company (MRC) ownership were mapped, and in the Sproul Creek basin, photographs were only available for areas in Barnum Timber Company (BTC) ownership and immediately adjacent areas. In these basins, the rate of sediment production from non-inner-gorge shallow landslides that was estimated for mapped areas was applied to all unmapped upland (non-inner-gorge) areas.

Due to time constraints, landslide mapping was not validated in the field. Field surveys would allow for more accurate estimates of landslide volumes and delivery ratios, estimates of the proportion of landslides not captured on aerial photographs, and collection of colluvial samples to estimate the grain-size distribution of mass wasting sediment inputs to stream channels. The mapping (including that by CDMG described below) likely resulted in underestimates of landsliding rates, given the omission of landslides that are not visible on aerial photographs (e.g., those that are small or obscured by canopy). Small streamside landslides that are not visible on aerial photographs may represent a significant sediment source. As part of its sediment source analysis in the Hollow Tree Watershed Assessment Unit (WAU) (which comprises areas of MRC ownership in the Hollow Tree ISA), MRC is developing estimates of sediment delivery from small streamside failures; these results will be available later in 1999.

Estimates of shallow landsliding based on CDMG mapping

Landslide sediment production for 1966–1981 was estimated by converting the following active slide features mapped by CDMG into sediment delivery volumes: point slides, active debris slides, and torrent tracks (debris avalanches). This conversion into sediment production estimates was based on several assumptions about the sizes of CDMG-mapped landslides. Point slides (i.e., those that appear on aerial photographs only as points and for which area therefore cannot be measured) on CDMG maps were assigned an average area of 400 m^2. The smallest polygon features on the CDMG maps are about 1,200 m^2 (with a mean of at least 2,000 m^2). In general, the smallest features visible on aerial photographs are about 100 m^2. Point slides therefore would have an average size between 100 m^2 and 1,200 m^2. Within this range, Stillwater Sciences selected an average area of 400 m^2 for point slides, which is also the average size of slides mapped by J. Coyle in the Caspar Creek basin (Dietrich et al. 1998). Assuming an average depth of 1.3 m and an average bulk density of 1.9 t/m^3 suggests average production of about 1,000 tons from individual CDMG point slides.

Active debris slides are depicted on CDMG maps as polygon features. The average area of these features was estimated by Stillwater Sciences using the digital version of the CDMG maps. Torrent tracks mapped by CDMG were assumed to produce 8 m^3/m (Benda and Cundy 1990), and volume values per track were added to the scar volumes of each debris torrent/avalanche.

Stillwater Sciences evaluated land-use and land-type association for shallow landslides depicted on CDMG maps by overlaying the digital CDMG map with our GIS road and channel coverages, resulting in landsliding rates for inner gorge, non-inner-gorge natural, road-related and upland landslides. GIS roads were buffered 20 m on each side of the road line to determine potential road-related slides, resulting in a 40-m road-effect width (it is acknowledged that some roads may have been constructed since 1981; however, the GIS coverage likely misses many roads that were present before 1981). A 100% delivery ratio was assumed for all active landslides (point slides, polygon debris slides, and debris avalanches/ torrents), based on Stillwater Sciences' assessment of greater than 90% delivery of landslides in the recent period in Hollow Tree, Tom Long, and Sproul Creek ISAs.

3.5.2 Earthflows and Associated Gullies

Earthflows, which are mainly associated with the Melange Matrix terrain but which also occur in Coastal Belt and Yager areas, are deep-seated mass movement features underlain by mechanically weak bedrock that result from the slow flow of saturated, clay-rich soil in a semi-viscous, highly plastic state (Swanston and Swanson 1976). Sediment production from earthflows was estimated by assuming that (1) sediment inputs are correlated with the length of stream channel bordered by these features, (2) the toes of deep-seated landslides entering channels actively erode at rates quantifiable by assumed average long-term movement rates and average bank (i.e., toe) heights. Stillwater Sciences measured the total length of earthflow toe stream banks depicted on CDMG (1984) geomorphic maps in the ISAs and in the SFEB. All earthflows mapped by CDMG were assumed to be active, based on field and aerial photograph observations by Stillwater Sciences. In addition, we assumed an average height of earthflow toes of 9 m, based on past studies in the Eel River basin (USDA 1970, USACE 1980, James 1983). Kelsey (1980) stated that earthflows (active and dormant) occupy 10% of Melange areas in the Van Duzen River basin.

Stillwater Sciences identified the extent and location of earthflows using CDMG geomorphic maps and aerial photograph mapping in the Sproul and Tom Long creek basins. For mapping in ISAs, Stillwater Sciences mapped only the toes of active features. Active slides show evidence of recent movement, such as fresh scarps, jackstrawed trees, displaced roads and stream channels, clusters of large rocks in the stream channels, and streams and gullies with extensive or accelerated bank erosion (USDA 1970). Kelsey (1980) noted that "active earthflow surfaces are severely disrupted by mass movement, they have a dense network of parallel or dendritic bare-walled rill and gully systems, the drainage pattern constantly changes because of continued earthflow movement...the smaller rills and gullies that drain the bowl-shaped earthflow heads merge downslope into one axial gully, as much as 3 to 4.5 m deep...."

Stillwater Sciences reviewed literature data on average rates of earthflow movement to assist in estimating sediment production from earthflows. Regional data sources indicate average movement rates of about 2.4–4 m/yr (Van Duzen River basin [Kelsey 1980]), 4 m/yr (Eel River basin [Scott 1973]), and 0.1 m/yr (Redwood Creek basin [Swanston et al. 1995]). Based on these results, we applied an average movement rate of 1 m/yr to earthflow toes. This movement rate was assumed to incorporate sediment production from natural gully erosion associated with earthflows. Kelsey (1977) indicated that well-developed gully systems are typically present on active earthflows and can produce more sediment than that produced by stream erosion of earthflow toes (Nolan and Janda [1995] indicated that less than 10% of earthflow erosion is delivered from earthflow-gully systems that develop in the more coherent [compared to the Van Duzen] rocks of the Redwood Creek basin). Rates of annual movement can vary substantially; annual earthflow movements of up to 29 m have been measured in northwestern California (Kelsey 1978, Nolan and Janda 1995), and a series of wet winters can accelerate movement rates.

We assumed that sediment production from earthflow features is natural, although roads or other activities that destabilize toes may accelerate sediment inputs to channels (Walter 1986, as cited in Redwood National and State Parks 1997). We know of no data that establish a link between deep-seated landslide (earthflow) sediment input and tree harvesting. Kelsey (1980) hypothesized that grazing and vegetation conversion from perennial, native species with long roots to annual, exotic species with short roots may have increased gullying on earthflow surfaces.

Other forms of deep-seated landsliding (e.g., translational-rotational failures) are also prevalent in the SFEB. Our high-resolution DEM data (4-m) for the reach of the South Fork Eel between Branscomb and Tenmile Creek revealed extensive deep-seated landsliding, suggesting that this erosional process may be more important than previously believed. The percent of these features that are active is unknown, however, complicating assessment of sediment production from deep-seated features. Aggradation induced by the 1964 flood may have destabilized and triggered accelerated movement of previously dormant deep-seated (translational-rotational) landslides.

Inspection of CDMG geomorphic maps (1984) of the entire SFEB shows an increasing density of deep-seated landslides to the north, which we hypothesize is likely a legacy of very rapid uplift rates that (in the last 1–2 million years) possibly resulted in pronounced landscape-wide translational/rotational deep-seated landsliding. Most of these features are currently dormant, although some may have been remobilized in recent decades because of aggradation.

3.5.3 Road Surface Erosion

Road surface erosion (sheetwash) was assessed using SEDMODL, a GIS/DTM-based road erosion model developed by Boise Cascade (1999). The model combines components of the Washington DNR surface erosion model (in which input data on road use, surfacing, and cutslope characteristics are required) with GIS tools. Raines (1998) used this model for assessment of road erosion in the South Fork Trinity TMDL; that analysis had the advantage of existing US Forest Service data on road attributes (e.g., use, surfacing, etc.). This type of existing data on roads was not available for the SFEB. Stillwater Sciences conducted limited field surveys to determine road attribute data and numerous simplifying assumptions were used in the application of SEDMODL. Methods used in SEDMODL are discussed further in Appendix B.

A road network coverage for the entire basin based on recently updated (1994) 1:24,000 USGS topographic maps and supplemented by timber harvesting plan (THP) roads was available from the California Department of Forestry and Fire Protection Fire and Resource Assessment Program (CDF/FRAP). This provided information on road density, stream crossings, and limited road attribute data. This road network was supplemented in some areas by other existing coverages of roads (e.g., Barnum Timber Company, Mendocino Redwood Company) and by aerial photograph mapping of roads (in the Tom Long Creek basin). Comparison of various roads coverages and limited field surveys by Stillwater Sciences indicated that many roads (up to 50%) are excluded from the CDF/FRAP coverage, likely resulting in underestimates of road surface erosion. Map 10 shows a comparison of various road coverages for the Hollow Tree Creek basin.

The delivery ratios (percent of road length that delivers sediment to streams) estimated by SEDMODL are relatively low (generally in the range of 8–12%) compared to those estimated by Stillwater Sciences during limited field surveys in the SFEB. Road segments surveyed by Stillwater Sciences had delivery ratios ranging from 0 to 66% and averaging 24%, with variations reflecting road location (upslope versus streamside) and maintenance. Surface erosion rates may therefore be substantially higher (as much as 2.5-fold higher) than estimated by SEDMODL, although we did not apply any correction factor and report the results generated by SEDMODL.

3.5.4 Road Crossing and Gully Erosion

Field observations by Stillwater Sciences, literature review, and conversations with local residents (J. Monschke, pers. comm., 1999) indicated that erosion related to road/stream crossings and road-related gullying are substantial sediment sources in the SFEB. By road gullying, we refer to hillslope gullies caused by road diversions of runoff, rather than gullying of the road tread. This type of erosion is typically not visible on aerial photographs and cannot be estimated using GIS-based methods, however, complicating efforts to estimate basin-wide erosion from road crossings and gullying. Stillwater Sciences adopted a simple method for developing crude estimates of road crossing and gullying erosion based on limited field observations.

Stillwater Sciences conducted limited field surveys in May 1999 in which road crossing and gully erosion were estimated. Roads were visited in the Hollow Tree, Tom Long, and Bull Creek basins. A total of about 17.5 km of road length was surveyed. For each road segment surveyed, estimates were made of the volume, age, and delivery ratio of road crossing and gully erosion (including associated fillslope erosion). Some road-related gullies were likely missed in the field, because such features (i.e., those on hillslopes below roads) may not be immediately visible from the road surface. Gullies were classified as less than or greater than 15 years old; only those features less than 15 years old were considered in developing sediment production estimates for the recent period. Age estimates were largely based on the characteristics of vegetation growing in the eroded areas. Some features likely originally formed more than 15 years ago and have enlarged since then. The total volume of sediment delivered to streams from each road segment was calculated, and the results from all segments were combined to create an average linear rate of sediment delivery from road crossing and gully erosion. This linear rate was applied to all roads, excluding ridge-top roads, depicted on GIS road coverages. We assumed that sediment delivery from ridge-top roads is minimal, as suggested by Rice (1991) for the Sproul Creek basin.

Before adopting the crude approach of a linear sediment production rate, Stillwater Sciences analyzed field data for correlations between sediment production from road crossings and gullying, geology, and topography (as represented by SHALSTAB). No correlations or process dependence were observed (i.e., volume was not a clear function of a SHALSTAB category or geology). Many of the sites where gullying was documented (and about half of the volume estimated) in the field were not associated with GIS road/stream crossings; therefore we did not use road/stream crossing density as a basis for extrapolation. As a result, a linear road rate was calculated by assessing total road length and dividing by total volume lost. The resulting linear rate was about 650 m^3 of crossing and gully erosion per kilometer of non-ridge road. Over a 15-year period and assuming a bulk density of 1.9 t/m^3, that results in a rate of about 82 t/km of road/yr.

Application of this rate to the total length of the road network in each ISA resulted in estimates of total sediment production from road crossing and gully erosion. This method does not differentiate between road maintenance practices or road construction standards (e.g., outsloped vs. inboard ditch), which can strongly influence this type of erosion, as plugged culverts are likely the primary cause of this type of erosion (e.g., Weaver et al. 1995). Results describing sediment delivery from road crossing and gullying should be considered as hypothetical, potential rates based on the road length in a given area; the actual magnitudes of sediment delivery are highly uncertain because of the crude assumptions used. The high proportion of sediment production attributed to this source (as presented below) is roughly consistent, however, with studies in the Redwood Creek basin, which indicated that road-related gullying accounted for approximately 20% of total erosion (Redwood National and State Parks 1997, Weaver et al. 1995).

An assessment of existing and potential road-related erosion from roads on US Bureau of Land Management (BLM) lands in the SFEB has been completed by Pacific Watershed Associates (PWA 1997). These surveys mapped and inventoried approximately 138 km (86 miles) of active and abandoned logging roads on BLM lands, which are concentrated in the upper SFEB, surrounding the mainstem in the general vicinity of Rattlesnake Creek. PWA (1998) assessed only sites where future sediment delivery was likely, however; total past sediment delivery from the surveyed roads was not assessed. The PWA (1997) results, while providing a guide to limiting future erosion problems on BLM roads, are therefore not comparable to the road crossing and gullying estimates that we developed.

3.5.5 Skid Trail Erosion

Skid trails may be an important sediment source, although remote assessment of sediment production from skid trails is difficult and budget was not available for extensive field assessment. Skid trail erosion is likely correlated with density of skid trail stream crossings (connectedness of skid trails to channels), which can be inferred from aerial photographs of recently harvested areas.

Estimates of skid trail erosion were developed based on preliminary results of a skid trail erosion assessment conducted by MRC in the Hollow Tree Creek basin and adjacent areas. MRC's estimates were differentiated between 1966–1978 and 1984–1996 (for the purposes of our analysis, we assumed the 1984–1996 rates applied to the 1981–1996 period). For estimating erosion from skid trails in other parts of the SFEB, where no data related to skid trail densities or sediment delivery are available, we applied the average unit-area skid trail erosion rate estimated by MRC for their lands in the Hollow Tree Creek ISA. The percentage of land occupied by skid trails in the Coastal Belt and Yager portions of the SFEB as a whole was hypothesized to be similar to the percentage in Hollow Tree, as suggested by qualitative observations by Stillwater Sciences of skid trail densities in the Hollow Tree ISA and the SFEB as a whole from 1976 and 1998 aerial photographs. MRC's unit-area rate was multiplied by the area defined as Coastal Belt or Yager geomorphic terrain in our watershed stratification, to derive a skid trail erosion estimate in tons/year. The extent of Coastal Belt and Yager areas roughly corresponds to area with forest vegetation and that therefore has likely been exposed to timber harvesting and skid trail construction. We tested this hypothesis by comparing our geomorphic terrain coverage (Map 4) with a GIS coverage of Landsat TM vegetation mapping for the SFEB (Fox et al. 1998). This comparison indicated that there is considerable overlap between the Coastal Belt and Yager terrains and areas classified in the following vegetation categories: late-seral conifer, conifer/hardwood and mixed hardwood, and early seral conifer, conifer/hardwood and mixed hardwood. We assumed that sediment produced from skid trails consisted of 90% fine sediment and 10% coarse sediment (Forest, Soil, & Water, Inc. et al. 1998).

No skid trail erosion was assigned to Melange areas. This is because grazing and residential use have been predominant land uses in the Melange areas, rather than timber harvesting. In addition, no skid trails were observed in Melange areas based on limited aerial photograph surveys by Stillwater Sciences.

3.5.6 Soil Creep

Soil creep, the gradual and progressive downslope movement of soil that is driven by gravity, weathering processes, rainsplash, and biogenic activity, also contributes to hillslope sediment production in the SFEB. Soil creep rates are influenced by drainage density, hillslope gradient, and soil diffusivity (a rate of downslope sediment transport; i.e., diffusion). Shallow soil creep operates in the upper portion of the soil profile. In the Melange Matrix terrain, the predominant creep process is mantle creep ("deep creep"). Mantle creep operates over that portion of the landscape in the Melange Matrix terrain that is not occupied by active earthflows (assumed to be about 95% of the landscape in the Melange Matrix areas of the SFEB).

SEDMODL was used to estimate soil creep. SEDMODL accounted for effects of hillslope gradient on shallow soil creep by applying different creep rates for channels bordered by slopes with greater than 30% gradients (0.002 m/yr) and less than 30% gradients (0.001 m/yr). Hillslope gradients in the ISAs were determined using 10-m DEMs, and channel lengths bordered by different slope classes were determined using the channel network created by Stillwater Sciences. For estimating sediment production from mantle creep, an average movement rate of 0.01 m/yr (with no variation by slope gradient) was combined with an assumed average bank height of 1.5 m and data on channel lengths bordered by non-earthflow Melange Matrix areas. The assumed average movement rate for mantle creep (0.01 m/yr) is based on regional data on deep creep movement (e.g., USDA 1970, Dwyer et al 1971, Swanston et al. 1995). SEDMODL methods for estimating sediment production from soil creep are described further in Appendix B.

The effects of timber harvesting, road construction, and grazing on soil creep rates are uncertain, although changes in root strength and hydrology caused by these land uses may increase creep rates (Swanston and Swanson 1976, Kelsey 1978). In this sediment source assessment, we assumed that all sediment production from creep is natural, and soil creep rates were assumed to be the same for both recent (1981–1996) and 1966–1981 periods. Errors in these assumptions are unlikely to have a significant effect on the overall sediment delivery estimates. In an area where erosion rates are currently as high as in the SFEB, soil creep and biogenic transport cannot be significant contributors to sediment inputs compared to overall inputs, given limits on the amount of soil that can be transported by these diffusive processes. More accurate estimates of soil creep than provided by SEDMODL could be generated by applying a soil diffusion model based on a non-linear diffusive transport law (Roering et al 1999), although high-resolution topographic data are necessary for this method.

3.5.7 Other Erosion Categories

A number of erosion sources were not explicitly evaluated in our analysis. Examples of these categories include non-road-related hillslope gullying, and alluvial bank and terrace erosion. Non-road-related gullying may be an important source of erosion on hillslopes in the Melange terrain, especially in areas where grazing occurs and where forests have been converted to grasslands. Several studies have identified bank erosion as an important sediment source in the SFEB (USDA 1970, LaVen 1987a), although definitions of bank erosion vary between studies and streamside landsliding (i.e., colluvial input) is sometimes incorporated (e.g., USDA 1970). Stillwater Sciences did not quantitatively evaluate bank erosion, but did review past bank erosion studies, some of which are discussed below with respect to the Bull Creek ISA (Section 4.2.4). Bank erosion was considered within the context of the processes described above, including in the shallow landslide category, where bank erosion occurs as streamside failures in inner gorges, and in the deep-seated landslide category, since erosion of deep-seated landslide toes is a form of bank erosion.

Stillwater Sciences delineated potential areas of active alluvial bank and terrace erosion. Areas shown on the geologic and geomorphic maps (Maps 3 and 4) as stream channel deposits and terrace deposits (based on James [1983] and CDMG [1984]) are those that are susceptible to alluvial bank and terrace erosion. These areas are concentrated along the lower mainstem SFE, which flows through a discontinuous valley fill, and along Bull Creek. Terraces may be an important sediment source in areas where streams are actively cutting into terraces and/or where roads contribute to terrace erosion.

3.5.8 Overview of Colluvial Characteristics in the South Fork Eel Basin

Stillwater Sciences reviewed information on the characteristics of colluvium in the SFEB in order to assess the relative percentage of coarse versus fine sediment that likely enters stream channels. This distinction is important because coarse and fine sediment inputs have different geomorphic and ecological effects. Regional data suggest that mass wasting inputs typically have a roughly 30:70 coarse:fine ratio, based on average colluvial size distributions (CDWR 1974, Forest, Soil, & Water, Inc. et al. 1998, Fiori et al. 1999). Stillwater Sciences assumed that this ratio applied to all mass wasting, including shallow and deep-seated landslides, road crossing and gully erosion, and shallow soil creep. Skid trail erosion was assumed to have a 90% fine fraction (Forest, Soil, & Water, Inc. et al. 1998). Road surface erosion was assumed to consist of 100% fine sediment (WFPB 1997).

Data on colluvial bulk densities were also reviewed to allow conversion of volumes (m^3) to mass (tons). USDA (1970) indicated an average bulk density of about 1.5 t/m^3, while Kelsey (1978, as cited in Short 1993) reports a bulk density of 1.9 t/m^3. Short (1993) proposed a bulk density of 1.5 t/m^3 for gullies in Cuneo Creek. Other sources report bulk densities within a similar range (Dwyer et al. 1971, Scott 1973, CDWR 1974, Kelsey 1977, USACE 1980, Raines 1991). A bulk density of 1.9 t/m^3 was applied to all processes excluding road sheetwash and shallow soil creep. A bulk density of 1.4 t/m^3 was applied to sheetwash and shallow soil creep erosion, because these processes deliver sediment only from the upper portion of the soil profile where bulk densities are typically lower.

3.6 GIS/DTM Methods

GIS and DTM methods were used extensively in the sediment source analysis. Stillwater Sciences created 10-m DEMs for the ISAs in order to facilitate improved hydrologic and geomorphic modeling. Pre-existing digital elevation data for the SFEB were at a 30-m scale; these 30-m data were used for SFEB-wide modeling purposes. Methods used in creating 10-m DEMs are described in Appendix A. One component of our GIS/DTM approach to sediment source analysis was application of the SHALSTAB model for predicting shallow landslide hazard, as described further in Section 2.2 and Appendix A.

Stillwater Sciences also created improved channel network data for ISAs by combining USGS hydrography (blueline channels, 1:24,000 scale, obtained from CDF/FRAP) with extension of the drainage network using a drainage-area threshold (10 ac [0.04 km^2]) and the 10-m DEM. This method results in a combined channel network that accurately represents both high-order channels (in low-gradient, floodplain regions) and low-order channels (in areas of steeper, ridge and valley topopraphy) and better captures full drainage densities. Data on complete channel networks is valuable for conducting sediment source analysis, particularly in terms of modeling sediment delivery to low-order channels. For example, estimates of road surface erosion require information on road/stream crossings and therefore on accurate representation of complete channel networks. Methods used in creating the full channel network are described in Appendix A.

We also acquired many existing GIS coverages. As discussed in previous sections, we made extensive use of the digital version of CDMG geomorphic maps for the SFEB, originally dated 1984 and based on 1981 aerial photographs and made available in digital format in 1999. Road coverages were obtained from a variety of sources, including: SFEB-wide coverage from CDF/FRAP, areas in BLM ownership from BLM, areas in Barnum Timber Company (BTC) ownership (in the Sproul Creek basin) from BTC, and areas in MRC ownership (in the Hollow Tree ISA) from MRC. These road coverages were used to estimate total road length in ISAs. We also obtained coverages from CDF/FRAP of Timber Harvesting Plans (THPs) filed with CDF between 1986 and 1997 in order to gain insight into recent harvest patterns. Additional coverages included CalWater planning watersheds and 1:500,000 geologic maps (USGS/CDMG).

GIS/DTM methods were used to extrapolate results of sediment source assessments in ISAs to the SFEB as a whole SFEB. This included classification of shallow landslides by SHALSTAB (log q/T) class as a basis for extrapolation and delineation of potentially active earthflow toes using the CDMG digital geomorphic maps. Methods used in extrapolation are discussed further in Section 4.4 and in Appendix A.

3.7 Summary of Assumptions Used in Sediment Source Assessments

Many assumptions were applied in developing estimates of sediment delivery from various sources, as described in the above descriptions of source categories. These assumptions are summarized below:
- All shallow landslides mapped on aerial photographs by Stillwater Sciences and CDMG were assumed to have an average depth of 1.3 m.
- For shallow landslides, the relative proportion of natural versus anthropogenic landslides was

estimated using the following criteria: (1) landslides associated with roads were identified as anthropogenic, (2) all non-road-related inner gorge slides were assumed to be natural, (3) all non-inner-gorge streamside slides were assumed to be natural, (4) all upland slides were assumed to be anthropogenic. The errors in these assumptions (i.e., overestimating the anthropogenic contribution to upland landsliding and underestimating anthropogenic contributions to inner gorge and other streamside failures) may counterbalance each other, resulting in reasonable overall estimates of the ratio of anthropogenic:total loading.

- Debris torrent tracks were converted from mapped length to volume assuming 8 m^3 of material removed per meter of torrent track (Benda and Cundy 1990).
- For estimating landslide sediment delivery during the 1966–1981 period, CDMG maps were used and assumed to represent that period. Stillwater Sciences assumed that features depicted as point slides delivered an average of 1,000 tons. For polygon features, area was estimated using the Stillwater Sciences GIS, and a delivery ratio of 100% was assumed.
- Active earthflows were assumed to move at a rate of 1 m/yr and to have average toe heights of 9 m. Earthflow sediment delivery was calculated as follows: (average movement rate [1 m/yr]) * (average toe height [9 m]) * (length of toe [as determined by mapping]). Sediment delivery by this calculation was assumed to incorporate gullies associated with earthflows. Translational/rotational deep-seated landslides in the SFEB were assumed to be dormant.
- Road crossing and gully erosion was calculated by multiplying an average unit-length rate of road crossing and gully erosion of 82 t/km/yr (as determined in the field from limited surveys) by non-ridge road length in a given subbasin.
- Skid trail erosion was calculated by applying unit-area rates estimated by MRC in the Hollow Tree ISA throughout other areas in the Coastal Belt and Yager geomorphic terrains. No skid trail erosion was assigned to Melange or Alluvial terrain areas.
- In calculations of soil creep production using SEDMODL, different rates of creep were assumed to operate in the Coastal Belt and Yager areas (shallow creep of 0.001 m/yr and 0.002 m/yr for channels bordered by slopes with less than and greater than 30% gradients, respectively) and Melange areas (mantle creep of 0.01 m/yr).
- Assumptions used in calculating road surface erosion with SEDMODL are discussed in Appendix B.
- Inputs from deep-seated landslides, road surface erosion, road crossing and gully erosion, and soil creep were assumed to be the same for each time period. This assumption is unrealistic for anthropogenic inputs from roads, given temporal variations in construction and maintenance practices, use levels, and densities, all of which cause variations in sediment inputs.
- For converting volumes (m^3) to mass (tons), a bulk density of 1.4 t/m^3 was applied to sheetwash (road surface) and shallow soil creep erosion, and a bulk density of 1.9 t/m^3 was applied to all other processes.
- Coarse versus fine sediment fractions of sediment inputs were estimated for all sources, as follows: earthflows, shallow landslides, road crossing and gully erosion, and soil creep were assigned a 30% coarse and 70% fine fraction; skid trails were assigned a 10% coarse and 90% fine fraction, and road surface erosion was assumed to consist of 100% fine sediment.

4. SEDIMENT SOURCE ANALYSIS RESULTS

The sediment source analysis results consist of four components, which are presented below: (1) summary of existing data on suspended sediment yield in the SFEB, (2) source analyses for ISAs, (3) extrapolation of these results basin-wide, and (4) summary of a sediment source analysis for the 1942–1965 period in the SFEB by USDA (1970).

4.1 Sediment Yield Data

Stillwater Sciences summarized data on suspended sediment yield for USGS stations in the SFEB, as reported in USACE (1980). These data provide a numeric constraint on sediment yield estimates and are summarized in Table 3. Total sediment yield estimates were based on the assumption that bedload is 15% of total load (after Sheppard 1963, Madej 1984). The bedload fraction of total load can be highly variable; studies from the Bull Creek basin have suggested possible bedload fractions ranging from 3% (LaVen 1987a) to 50% (Short 1993). Estimates of suspended sediment yield reported in Table 3 may underestimate actual yield; Ferguson (1986) found that traditional suspended sediment sampling techniques (as were used in developing the results in Table 3) may underestimate the actual suspended sediment load by up to 50% by failing to adequately account for the effects of high flows.

Table 3. Summary of suspended sediment yield data for gaging stations in the South Fork Eel basin.

Station	Drainage Area	Period of Record	Suspended Sediment Yield (t/yr)	Unit-Area Suspended Yield ($t/km^2/yr$)	Unit-Area Total Yield ($t/km^2/yr$)
South Fork Eel at Miranda	1390 km^2 (537 mi^2)	1958–1962	1,774,000	1276	1467
		1941–1965[1]	2,080,000	1496	1720
South Fork Eel at Branscomb	114 km^2 (43.9 mi^2)	1958–1970	108,700	954	1097
		1958–1962	89,200	783	900
		1941–1965[1]	77,000	676	777
Bull Creek at Weott	73 km^2 (28 mi^2)	1976–1979	220,170	3026	3480
Elder Creek	17 km^2 (6.5 mi^2)	1974–1975	11,300	671	772

1 Results for 1941–1965 are based on extrapolation from period of record over 1941–1965 period using sediment to discharge rating curves and are reported in USDA (1970).

Only one USGS gaging station in the SFEB, South Fork Eel at Branscomb, includes the 1964 flood in its period of record. Data from elsewhere in the Eel River basin provide insight into the contribution of the 1964 flood event to average sediment yield over longer periods. Brown and Ritter (1971, as cited in Lisle 1990) indicate that at the Eel River at Scotia station, about 20% more suspended sediment yield occurred in three days during the December 1964 event than had occurred in the preceding 8 years. Kelsey (1980) estimates that in the Van Duzen River basin, the 1964 storm caused about 50% more sediment delivery during the 1941–1975 period than would have occurred during this period without the 1964 storm.

Data from USGS gaging stations in the Eel River basin outside the SFEB with longer periods of record, as reported in USACE (1980), were also evaluated. The stations with the longest periods of record (1958–1976) are the Eel River at Scotia, Middle Fork Eel at Dos Rios, and Van Duzen River near Bridgeville. The average unit-area suspended sediment yields from these three stations were 3,210 t/km^2/yr, 1,980 t/km^2/yr, and 3,820 t/km^2/yr, respectively, for the 1958–1976 period. Figure 1 shows suspended sediment yield for selected stations in the Eel River basin, including stations in the SFEB.

USDA (1970) combined discharge data and suspended sediment data for a limited number of years to derive sediment yield estimates for the 1941–1965 period. In the SFEB, rating curves were developed for the Branscomb and Miranda stations, based on suspended sediment data collected at these stations from 1958 to 1965 (Branscomb) and 1958 to 1962 (Miranda). Extrapolated to the 1941–1965 period, these data suggest that suspended and total sediment yield at the SFE at Branscomb station (43.9 mi^2) averaged 675.6 t/km^2/yr and 777 t/km^2/yr, respectively. At the SFE at Miranda station (537 mi^2), suspended and total sediment yield averaged 1,496 t/km^2/yr and 1,720 t/km^2/yr, respectively, from 1941–1965. These results assume that bedload constitutes 15% of the total load (after Sheppard 1963). This method assumes that the relationship between suspended sediment concentration and discharge does not vary and is therefore insensitive to land use effects on suspended sediment. Suspended discharge studies on Redwood Creek basin by Nolan and Janda (1981) indicated that suspended sediment discharge following timber harvest increases 10-fold and, to some degree, the increase persists for at least a decade (as cited in Short 1993).

Based on analysis of suspended sediment yield data from the Eel River basin, including the SFEB, USDA (1970) concluded that sediment yield progressively increases toward the ocean as the watershed size increases, which is the opposite of most areas in the United States (USDA 1970). In general, precipitation and runoff in the Eel River basin, including the SFEB, increases from south to north and from east to west. USACE (1980) noted that the increase in unit-area suspended sediment yield with drainage area in the Eel River basin is caused by earthflow inputs to high-order channels. The increase in sediment yield with increasing drainage area may be related to re-activation of dormant deep-seated landslides, which are most prevalent in the northern portion of the SFEB, by flood-related aggradation in the past few decades, as suggested by Lisle (1981, 1990) and Kelsey (1977) for the northern California Coast Range.

4.1.1 Discharge Data/Storm History

Stillwater Sciences also summarized discharge data from the SFE near Miranda gage, which has the longest period of record of gaging stations in the SFEB (1941 to present) and the largest contributing drainage area (1390 km^2). This analysis provided information on the occurrence of large discharge events and on the temporal pattern of wet and dry periods. Figures 2 and 3 show annual water yield and annual peaks for the SFE near Miranda gage. These figures show that the 1983 water year experienced the highest total runoff during the period of record, and that the largest peak event occurred in the 1965 water year (December 1964). Fiori et al. (1999) provided additional information on storm and flood history in the Bull Creek basin, as summarized in Section 4.2.4 below.

The time periods assessed in our sediment source analysis both experienced multiple storm events that were likely large enough to trigger landsliding. Analysis of discharge records indicated that during the

Figure 1: Suspended sediment yield for selected stations in the Eel River basin

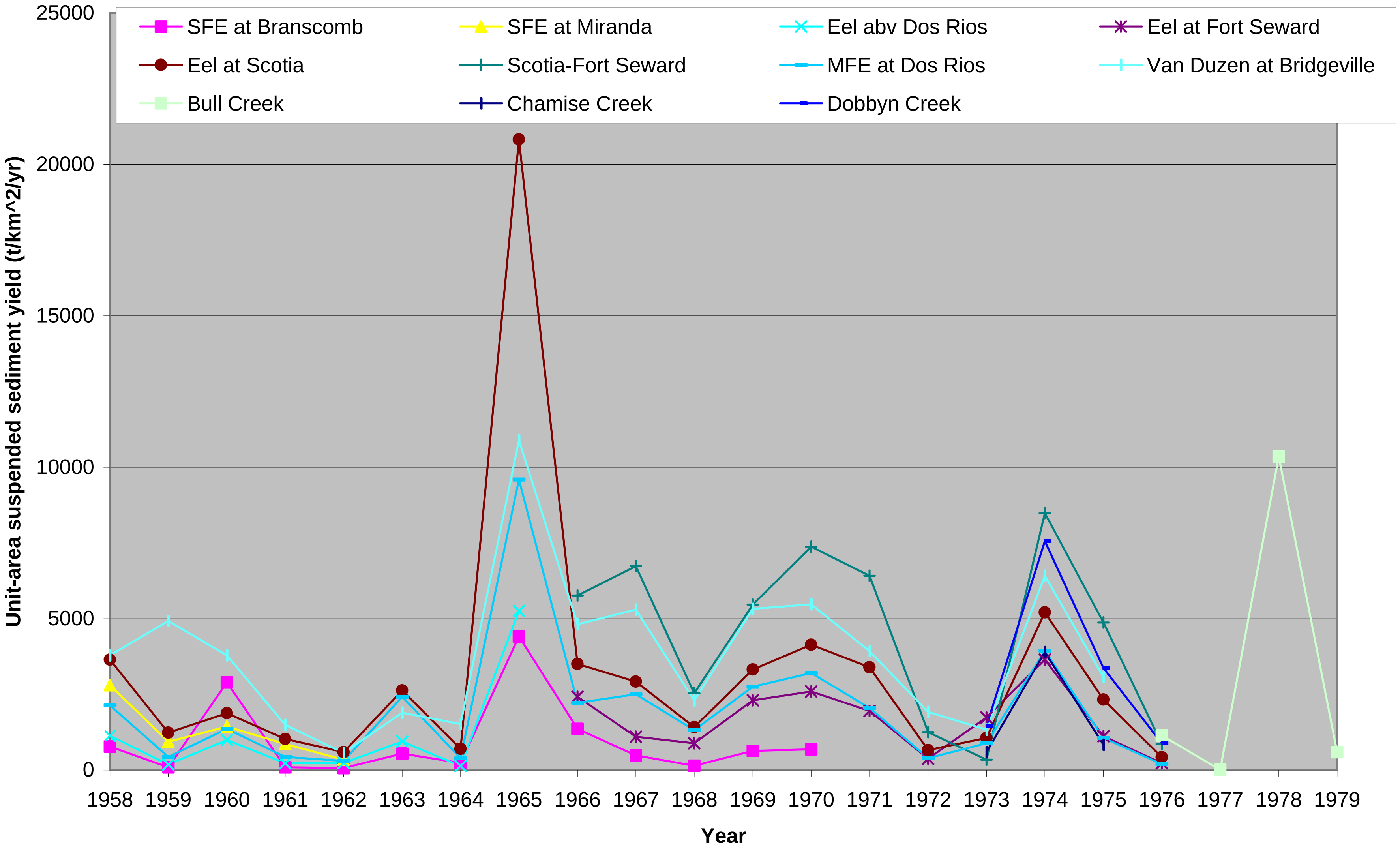


Figure 2: Total annual runoff, South Fork Eel River near Miranda

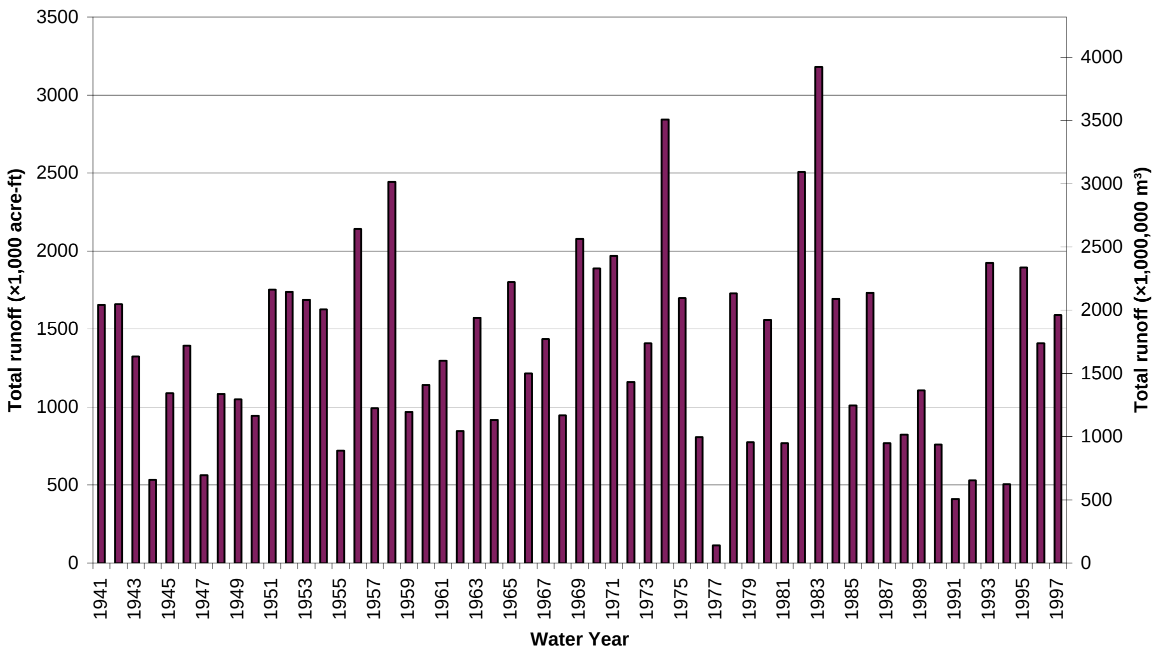
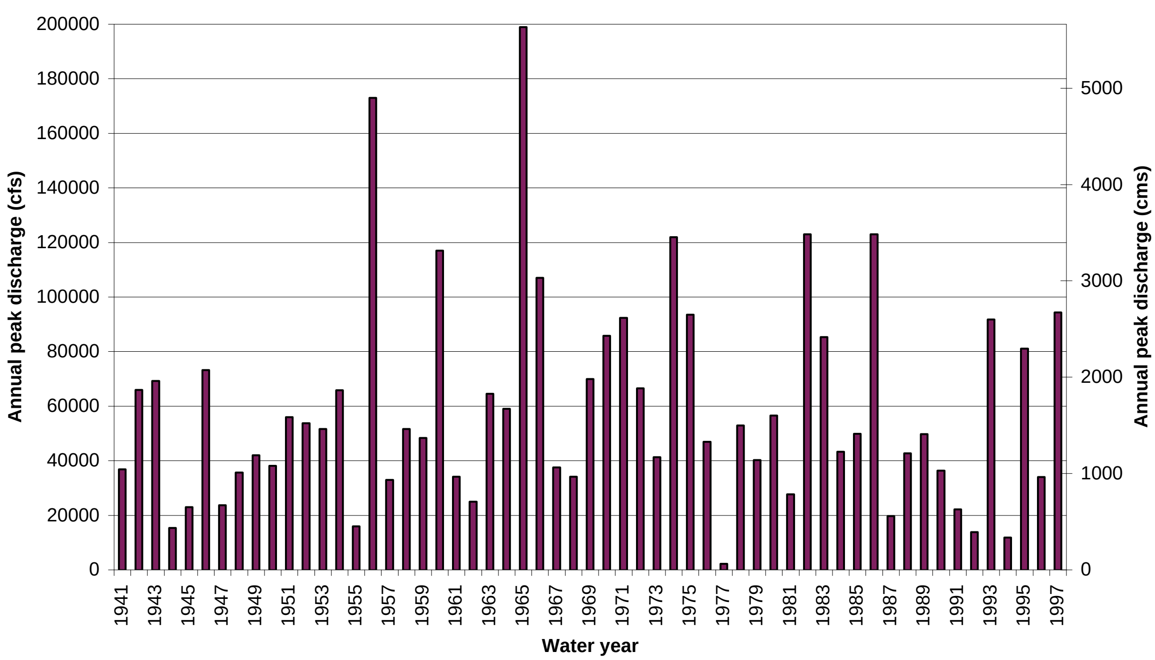


Figure 3: Annual peak discharge, South Fork Eel River near Miranda



1966–1981 period, potentially landslide-triggering storms occurred in 1966 and 1974, and possibly in 1971 and 1975 (Figure 3). In the recent period (defined as 1981–1996 in the sediment source analysis), large storms occurred in 1982, 1986, 1993, and 1995 (Figure 3). Overall, the 1966–1981 period was wetter than the 1981–1996 period, which included a drought period in the late 1980s and early 1990s (Figure 2). Various authors have defined different possible forcing thresholds for what constitutes a landslide-triggering storm event (Cafferata and Spittler 1998, Caine 1980, Cannon and Ellen 1985), although in most cases available precipitation data for stations in the SFEB (including data on antecedent precipitation before storms) were not sufficient for rigorously assessing the frequency of triggering events according to the various thresholds in the literature.

4.2 Sediment Source Assessment Results for Intensive Study Areas

A main component of our analysis was sediment source assessments for each ISA that was selected to represent different geomorphic terrains in the SFEB. The areas selected were Hollow Tree Creek, Tom Long Creek, Sproul Creek, and Bull Creek. Characteristics of these areas are shown in Tables 4 and 5. As noted above in Section 3.3, areas chosen for intensive study were among the few areas to which we had access for field study and the cooperation of landowners. Estimates of anthropogenic contributions to total sediment loading in these areas are not intended to single out the landowners in these areas. Moreover, the coarse resolution of our analysis, the limited time available for field surveys, and the reliance on many assumptions in assessing sediment sources and causality reduced our ability to differentiate between effects of various land management practices on geomorphic processes.

Table 4. Summary of intensive study area characteristics, based on Stillwater Sciences' GIS/DTM.

Intensive Study Area	Geomorphic Terrain	Drainage Area (km^2)	Channel Length (km)	Drainage Density (km/km^2)	Road Length (km)	Road Density (km/km^2)	No. of Road/ Stream Crossings	Stream Crossing Density ($no./km^2$)	Inner Gorge Length (km)
Hollow Tree	Coastal Belt	159	408.7	2.57	350.4	2.2	477	3.0	12.0
Tom Long Creek	Coastal Belt/ Melange	34.1	99.5	2.92	97.5	2.9	89	2.6	2.5
Sproul Creek	Coastal Belt/ Yager	62.3	166.5	2.67	200.4	3.2	188	3.0	7.5
Bull Creek	Yager	112.3	290.9	2.59	135.4	1.2	124	1.1	18

Table 5. Summary of 10-m SHALSTAB results for Intensive Study Areas and 30-m results for South Fork Eel Basin.

Intensive Study Area[1]	log q/T Value and Hazard Class																	
	Chronic Instability		< –3.1 High		–3.1 to –2.8 Moderately High		–2.8 to –2.5 Moderate		–2.5 to –2.2 Moderately Low		–2.2 to –1.9 Low		–1.9 to 9.9		Stable		Total	
	Area (km^2)	% of Total	Area (km^2)	% of Total	Area (km^2)	% of Total	Area (km^2)	% of Total	Area (km^2)	% of Total	Area (km^2)	% of Total	Area (km^2)	% of Total	Area (km^2)	% of Total	Area (km^2)	% of Total
Sproul	0.0079	0.01	1.35	2.09	2.26	3.50	5.88	9.12	9.28	14.39	5.69	8.82	0.89	1.38	39.15	60.69	64.51	100
Tom Long - Coastal Belt	0.0896	0.31	1.53	5.29	1.62	5.64	3.63	12.60	4.53	15.73	1.85	6.40	0.18	0.63	15.39	53.40	28.82	100
Tom Long - Melange	0.0018	0.03	0.09	1.29	0.11	1.61	0.32	4.54	0.48	6.84	0.21	2.92	0.02	0.28	5.80	82.49	7.03	100
Bull	0.16	0.15	4.44	3.97	6.07	5.43	11.08	9.90	10.68	9.54	4.42	3.95	0.58	0.52	74.52	66.56	111.95	100
Hollow Tree	0.68	0.43	6.24	3.93	8.77	5.52	20.74	13.06	31.29	19.70	19.78	12.46	4.16	2.62	67.12	42.27	158.78	100
South Fork Eel Basin[2]	1.37	0.10	67.20	3.80	103.30	5.80	198.70	11.10	187.40	10.50	44.00	2.50	0.05	0.00	1,180.90	66.20	1,782.90	100

1 Results for subbasins based on 10-m DEM

2 Results for South Fork Eel basin based on 30-m DEM

4.2.1 Hollow Tree Intensive Study Area

The Hollow Tree ISA consists of the Hollow Tree Creek basin and small adjacent tributary basins (Low Gap Creek, Mill Creek) that enter the South Fork Eel River directly. This ISA has an area of 159 km^2 (61 mi^2) and is located in the southwest corner of the SFEB (Maps 1, 6). Most of this ISA is owned by Mendocino Redwood Company (MRC), which provided access for field studies and shared data that they have collected. The areas included in the Hollow Tree ISA represent a slight modification of the area delineated as the Hollow Tree Creek Watershed and Wildlife Assessment Area (WWAA 41) in the Louisiana-Pacific Sustained Yield Plan (Louisiana-Pacific 1997); the original WWAA 41 area of 143 km^2 (55 mi^2) was buffered along its boundaries by Stillwater Sciences to facilitate GIS analysis. Existing information about this area includes a Level I watershed analysis of the Hollow Tree WWAA developed by Louisiana-Pacific (the previous owners) as part of a Sustained Yield Plan (Louisiana-Pacific 1997). MRC is currently conducting a Level II watershed analysis in areas of its ownership in the Hollow Tree ISA. Preliminary results were provided to Stillwater Sciences by MRC and are presented below; these data are subject to revision pending completion of MRC's Level II watershed analysis and sediment source assessment, which will be finalized in 2000.

The Hollow Tree ISA is underlain by the Coastal Belt Franciscan terrain. This ISA is drained primarily by Hollow Tree Creek and its tributaries, which include Middle Creek, Bear Wallow Creek, Bond Creek, Redwood Creek, and Huckleberry Creek. Hollow Tree Creek flows into the South Fork of the Eel River immediately upstream from the town of Leggett. The average annual precipitation in the Hollow Tree ISA is approximately 69 inches (175 cm) (Rantz 1968). Approximately 95% of the precipitation is recorded from October through May. January is the wettest month, when about 18% of the average annual total is recorded at the stations. The dominant land-cover type within the ownership is coniferous forest (Louisiana-Pacific 1997).

The MRC ownership within the Hollow Tree ISA comprises 82 km^2 (32 mi^2) or slightly more than half of the total ISA area. The proportion of MRC ownership is highest in the Middle Hollow Tree Creek planning watershed (89%) and lowest in the Low Gap Creek planning watershed (17%). Land use in the ISA is predominantly timber production, with a few residences and vacation homes along Hollow Tree Creek (Louisiana-Pacific 1997). Areas owned by MRC were intensively logged in the 1970s under Louisiana-Pacific ownership. Levels of timber harvest in the 1980s and 1990s have been substantially lower.

Results of Stillwater Sciences' Sediment Source Analysis for the Hollow Tree ISA
Stillwater Sciences constructed a sediment source analysis for the Hollow Tree ISA largely by using preliminary results from MRC's Level II watershed analysis. MRC mapped landslides using 1978 and 1996 aerial photographs in areas of their ownership (slightly more than half of the total area of the Hollow Tree ISA) and carried out field validation in June 1999. The MRC mapping provided volume estimates and identification of causality, although the MRC system for classifying causality differed slightly from that used by Stillwater Sciences. Stillwater Sciences analyzed the MRC landslide data and re-delineated landslides to match our system (inner gorge, road-related, non-inner-gorge natural, non-road management [upland] landslides). Some slides classified as "inner gorge" by MRC were re-classified as streamside non-inner-gorge by Stillwater Sciences if they occurred outside of those areas delineated by Stillwater Sciences as inner gorges. In addition, some slides not classified as road-related by MRC were classified as

road-related if our GIS roads coverage overlay indicated proximity of roads to the landslides.

MRC also provided estimates of skid trail erosion based on 1978 and 1996 aerial photograph mapping, which included estimates of the percentage of the landscape occupied by active skid trails, the number of skid trail stream crossings per unit area, and the length of stream used for skidding. MRC also applied predictive equations for sediment delivery from roads that are outlined in the Washington DNR surface erosion module (WFPB 1997) in order to calculate skid trail erosion. MRC will also conduct a road surface erosion assessment based on Washington DNR methods, results of which will be produced in 2000. To provide interim estimates of road surface erosion for this sediment source assessment, we applied SEDMODL; these results should be updated with MRC's when the latter are available.

Current conditions (1978–1996)
Based on 1996 aerial photographs and 1999 field surveys, MRC mapped 206 landslides, including definite, probable, and questionable features, over an area of 82.25 km^2. Stillwater assumed that this mapping represented an 18-year period, from 1978 to 1996, although some landslides occurring since 1996 were added based on field surveys. The results of this mapping and of Stillwater Sciences' re-classification of landslides are shown in Table 6. These results suggest that of all landslide sediment delivery, about half was road-related, and about 28% was natural during the 1978–1996 period. The delivery ratio to channels of sediment mobilized on hillslopes is 97% (396,595 t were produced from all slides, and 385,810 t were delivered in areas of MRC ownership).

Table 6. Summary of landslide results in Hollow Tree ISA, 1978–1996, based on Stillwater analysis of mapping by Mendocino Redwoods Company.

Type	Number of Landslides	Total Volume Delivered (m^3)	Total Mass Delivered (t)	Average Delivery for Mapped Area (t/yr)	Land Type Area (km^2)	Average Land Type Unit-Area Delivery (t/km^2/yr)	Total Delivery for Whole ISA (t/yr)
Inner gorge natural	26	13,390	25,441	1,413	4.5	314	1,885
Streamside natural	20	43,202	82,084	4,560	77.75	58.7	8,573
Upland "management"	69	44,469	84,491	4,694	77.75	60.4	8,824
Road-related uplands	70	59,529	113,105	6,284	77.75	80.8	11,812
Road-related inner gorge	21	42,468	80,689	4,483	4.5	996	5,977
Total road-related	91	101,997	193,794	10,767	82.25	131	17,789
Total	**206**	**203,058**	**385,810**	**21,444**	**82.25**	**261**	**37,071**

The skid trail assessment by MRC indicated very low rates of sediment delivery from skid trails under current conditions (16 t/km^2/yr, or 2435 t/yr for MRC ownership in the Hollow Tree ISA) (MRC 1999). This reflects the low level of new skid trail construction and use in the Hollow Tree ISA during the 1980s and 1990s; the small amount of sediment delivery estimated for the recent period was deemed to be attributable to legacy effects of old skid trails.

Stillwater Sciences quantified delivery from other sources of sediment, including road surface erosion, shallow soil creep, deep-seated landslide erosion, and road crossing and gully erosion, using the methods and assumptions outlined above. SEDMODL indicated a road surface erosion rate of 5821 t/yr, with 12.5% of road length delivering to channels. Road crossing and gully erosion was estimated to account for about 28,000 t/yr, based on a non-ridge road length of 340 km. This rate was based in part on road surveys by Stillwater Sciences in the Hollow Tree Creek basin, including roads along Redwood, Bear Wallow, Bond, Upper Hollow Tree, and Hollow Tree creeks. These surveys documented large road-related gullies in some locations, particularly in the Bear Wallow Creek subbasin. Shallow soil creep was estimated using SEDMODL, which indicated creep production of 1173 t/yr (7 t/km^2/yr).

A small number of active deep-seated landslides (earthflows) were documented in the Hollow Tree ISA, based on analysis of CDMG maps, limited aerial photograph inspection, and field observations. This analysis suggested a total length of deep-seated landslide toes adjacent to stream channels of 2,100 m, resulting in delivery of 35,910 t/yr (236 t/km^2/yr over the ISA [152.2 km^2]). Overall, sediment loading during the 1978–1996 period in Hollow Tree was about 110,000 t/yr, or 693 t/km$^{2/}$yr, and the ratio of anthropogenic:total loading was 0.57. These results are summarized in Table 7 (attached).

1966–1978 period

Compared to 1996 aerial photographic mapping combined with 1999 field surveys, MRC mapped a smaller number of landslides on 1978 aerial photographs. Stillwater Sciences assumed that these photographs represent the 1966–1978 period in order to develop results that are comparable to the 1966–1981 period assessed for other ISAs. A total of 177 landslides were mapped by MRC over an area of 82.2 km^2, including features identified with “definite,” “probable,” and “questionable” certainties. These features were estimated to have an overall delivery ratio of 95% by Stillwater Sciences, based on MRC’s landslide inventory. Results of landslide mapping for 1966–1978 are summarized in Table 8.

Table 8. Summary of landslide results in Hollow Tree ISA, 1966–1978, based on Stillwater Sciences’ analysis of mapping by Mendocino Redwoods Company.

Type	Number of Landslides	Total Volume Delivered (m^3)	Total Mass Delivered (t)	Average Delivery for Mapped Area (t/yr)	Land Type Area (km^2)	Average Land Type Unit-Area Delivery (t/km^2/yr)	Total Delivery for Whole ISA (t/yr)
Inner gorge natural	25	72,389	137,539	11,462	4.5	2,547	15,282
Streamside natural	15	12,332	23,431	1,953	77.75	25.1	3,671
Upland “management”	54	35,427	67,311	5,609	77.75	72.1	10,545
Road-related uplands	52	39,116	74,320	6,193	77.75	79.7	11,643
Road-related inner gorge	31	85,034	161,565	13,464	4.5	2,992	17,952
Total road-related	83	124,150	235,885	19,657	82.25	239	29,595
Total	**177**	**244,308**	**464,166**	**38,681**	**82.25**	**47.0**	**59,093**

The skid trail assessment by MRC indicated high rates of sediment delivery from skid trails during the 1966–1978 period (107 t/km^2/yr, or 16280 t/yr for the ISA). This reflects the logging practices in Hollow Tree during that time, which were characterized by intensive tractor logging and construction of skid trails adjacent to or in low-order streams.

Stillwater Sciences assumed that rates of road surface erosion, road crossing and gully erosion, soil creep, and deep-seated landslide inputs were the same in 1966–1978 as in the recent period. It is acknowledged that road-related erosion (surface erosion and crossing and gully erosion) were likely higher during the 1966–1978 period, given the intensive timber harvesting during that period and the improved road maintenance practices during the recent period. Overall, sediment loading during the 1966–1978 period in Hollow Tree was 154,700 t/yr, or 971 t/km^2/yr, and the ratio of anthropogenic:total loading was 0.64. These results are summarized in Table 7 (attached).

A rough assessment of the accuracy of these results can be made by comparison with sediment yield data from the USGS SFE at Branscomb station, which is located near the Hollow Tree Creek basin (along the mainstem SFE upstream of the Hollow Tree Creek confluence), for the 1958–1970 period. Average sediment yield at Branscomb during that time was about 1,100 t/km^2/yr, and average yield at that station from 1966–1970 (the period of overlap with our assessment period of 1966–1978) was about 760 t/km^2/yr. Although the 1958–1970 and 1966–1978 periods are not strictly comparable, given discharge variations and the occurrence of the 1964 flood in the former period, this comparison does suggest that the Stillwater estimates for the Hollow Tree ISA are within a reasonable range of measured sediment yields in the upper SFEB (as represented by the Branscomb gaging station) during this time period.

Comparison of landslide mapping by CDMG (1981 aerial photographs) and MRC (1978 photographs)
Stillwater Sciences compared landslide mapping by MRC based on 1978 photographs (assumed to represent 1966–1978) with mapping by CDMG using 1981 aerial photographs (assumed to represent 1966–1981) in the Hollow Tree ISA. This comparison allows a means of evaluating the accuracy of these two mapping efforts and of testing the validity of our method for estimating shallow landslide sediment production using CDMG maps, as applied in other ISAs for the 1966–1981 period.

CDMG mapping based on 1981 aerial photographs (assumed to represent the 1966–1981 period) showed 422 point slides and 89 polygon landslides in the area of MRC ownership in the Hollow Tree ISA (82.2 km^2). The total areas for the polygon slides, as indicated by Stillwater Sciences GIS analysis, was 122,500 m^2 in the area we delineated as inner gorge and 301,000 m^2 in non-inner-gorge areas (423,500 m^2 total). If an average area of 400 m^2 per point slide is assumed (as explained in Section 3.5.1), this suggests a total area of 592,300 m^2 for CDMG point and polygon slides, or an average area per landslide of about 1,160 m^2 (592,300 m^2/511 slides). This is the same as the average landslide area estimated by MRC for 1978 landslides, based on total landslide area of 204,900 m^2 and 177 slides (MRC 1999). This comparison suggests that our estimates of the area of CDMG landslides, including our assumptions about average area of point slides, are reasonable.

Although average landslide areas were similar, CDMG mapped approximately 3 times as many landslides, with a total area about 3 times greater than that of the MRC landslides. Comparison of GIS coverages of the MRC and CDMG landslides indicates that CDMG polygon slides were generally also mapped by MRC, but that many point slides mapped by CDMG (including many that appeared to have some road association

Table 7.

Hollow Tree Creek ISA, 1978-1996: sediment source analysis results

Sediment Source	Total sediment input, t/yr	Unit-area sediment input (t/km2/yr)	Fraction of total	Coarse sediment input, t/yr	Fine sediment input, t/yr	Fine:total ratio	Natural input, t/yr	Anthropogenic input, t/yr	Anthropogenic coarse input, t/yr	Anthropogenic fine input, t/yr	Anthro: Total sediment input ratio	Anthro: Total fine sediment input ratio	Anthro: Total coarse sediment input ratio
Earthflow toes and associated gullies	35910	225	0.33	10773	25137	0.7	35910	0	0	0	0	0	0
Inner gorge MW, natural	1885	12	0.02	566	1320	0.7	1885	0	0	0	0	0	0
Streamside (non-inner-gorge) MW	8573	54	0.08	2572	6001	0.7	8573	0	0	0	0	0	0
Road-related MW	17789	112	0.16	5337	12452	0.7	0	17789	5337	12452	1	1	1
Upland MW	8824	55	0.08	2647	6177	0.7	0	8824	2647	6177	1	1	1
Road surface erosion	5821	37	0.05	0	5821	1	0	5821	0	5821	1	1	0
Road crossing and gully erosion	27990	176	0.25	8397	19593	0.7	0	27990	2799	25191	1	1	0
Skid trail erosion	2435	15	0.02	244	2192	0.9	0	2435	244	2192	1	1	1
Soil creep	1173	7	0.01	352	821	0.7	1173	0	0	0	0	0	0
Total	**110400**	**693**	**1**	**30887**	**79513**	**0.72**	**47541**	**62859**	**11026**	**51833**	**0.57**	**0.65**	**0.36**

Hollow Tree Creek ISA, 1966-1978: sediment source analysis results

Sediment Source	Total sediment input, t/yr	Unit-area sediment input (t/km2/yr)	Fraction of total	Coarse sediment input, t/yr	Fine sediment input, t/yr	Fine:total ratio	Natural input, t/yr	Anthropogenic input, t/yr	Anthropogenic coarse input, t/yr	Anthropogenic fine input, t/yr	Anthro: Total sediment input ratio	Anthro: Total fine sediment input ratio	Anthro: Total coarse sediment input ratio
Earthflow toes and associated gullies	35910	225	0.25	10773	25137	0.7	35910	0	0	0	0	0	0
Inner gorge MW, natural	15282	96	0.10	4585	10697	0.7	15282	0	0	0	0	0	0
Streamside (non-inner-gorge) MW	3671	23	0.03	1101	2570	0.7	3671	0	0	0	0	0	0
Road-related MW	29595	186	0.20	8879	20717	0.7	0	29595	8879	20717	1	1	1
Upland MW	10545	66	0.07	3164	7382	0.7	0	10545	3164	7382	1	1	1
Road surface erosion	5821	37	0.04	0	5821	1	0	5821	0	5821	1	1	0
Road crossing and gully erosion	27990	176	0.19	8397	19593	0.7	0	27990	2799	25191	1	1	0
Skid trail erosion	16281	102	0.11	1628	14653	0.9	0	16281	1628	14653	1	1	1
Soil creep	1173	7	0.01	352	821	0.7	1173	0	0	0	0	0	0
Total	**146268**	**918**	1.00	**38878**	**107390**	**0.73**	**56036**	**90232**	**16469**	**73763**	**0.62**	**0.69**	**0.42**

based on overlaying the GIS road coverage) were not mapped by MRC, suggesting either undermapping by MRC and/or overmapping by CDMG. If similar average landslide depths (i.e., 1.3 m) and bulk densities (1.9 t/m^3) are assumed for MRC and CDMG landslides, the difference in landslide areas between MRC and CDMG slides would result in approximately 3 times greater landslide sediment production based on the CDMG 1981 mapping compared to the MRC 1978 mapping. The difference likely is not attributable to landsliding between 1978 (aerial photographs mapped by MRC) and 1981 (aerial photographs mapped by CDMG), which were below-normal to normal runoff years without any large peak-flow events (Figures 2, 3). The results of the comparison of MRC and CDMG mapping are not conclusive (Stillwater Sciences did not have 1978 or 1981 aerial photographs of the Hollow Tree ISA for validating landslide mapping by either CDMG or MRC), but they do indicate that our method of estimating the size of CDMG slides is reasonable.

Discussion of Results for Hollow Tree ISA

The sediment source assessment for the Hollow Tree ISA indicates that sediment inputs are approximately 25% lower in the recent period (1978–1996) than in the 1966–1978 period. The ratio of anthropogenic to total loading has declined slightly as well, from 0.62 in the earlier period to 0.57 in the recent period. The results for the Hollow Tree ISA are sensitive to the assumptions applied for calculating earthflow inputs and road crossing and gully erosion, which are discussed in Sections 3.5 and 3.7 above. These two categories represent the largest sources during both periods (1966–1978 and 1978–1996), accounting for 58% of delivery in the former period and 44% in the latter period, when landsliding inputs were greater. Our estimates of production from earthflows and road crossing and gullying have considerable uncertainty compared to estimates of landslide and skid trail erosion inputs, which are based on preliminary results of analysis by MRC that incorporated considerably more field work and aerial photograph interpretation than the Stillwater estimates.

4.2.2 Tom Long Creek Basin

The Tom Long Creek basin is a 34 km^2 (13 mi^2) watershed in the eastern portion of the SFEB and is one of the larger tributaries to the East Branch South Fork Eel River (Maps 1, 8). This basin contains a mixture of Melange (7 km^2) and Coastal Belt Franciscan (27 km^2) terrain and includes grasslands (both natural and converted) and conifer-hardwood forests. Land uses historically included grazing and small-scale timber harvesting. Many areas in the basin were subdivided for residential use in the 1970s. Most of the basin is in dispersed private ownership, although a small portion is owned by BLM, including areas with old-growth Douglas-fir. The Tom Long Creek basin was selected as an ISA because it contains some Melange terrain, because it is distinct from other the ISAs in terms of geography and land use, and because we were able to acquire access for limited field studies.

Unlike for other ISAs we have assessed in the SFEB, no previous studies are available on sediment sources or land use history in the Tom Long Creek basin. The sediment source analysis therefore relied on aerial photograph and field analysis and on GIS/DTM methods. Stillwater Sciences obtained 1996 aerial photographs (1:24,000, black and white) and mapped 100% of the basin; mapping methods are described above in Section 3.5.1 and 3.5.2. In addition, Stillwater Sciences constructed a 10-m DEM coverage (see Appendix A) and supplemented the road coverage obtained from CDF/FRAP with roads we observed in the field and on aerial photographs that are not depicted on existing coverages.

Table 9.

Tom Long Creek basin, 1981-1996: sediment source analysis results

Sediment Source	Total sediment input, t/yr	Unit-area sediment input (t/km2/yr)	Fraction of total	Coarse sediment input, t/yr	Fine sediment input, t/yr	Fine:total ratio	Natural input, t/yr	Anthropogenic input, t/yr	Anthropogenic coarse input, t/yr	Anthropogenic fine input, t/yr	Anthro: Total sediment input ratio	Anthro: Total fine sediment input ratio	Anthro: Total coarse sediment input ratio
Earthflows toes and associated gullies	27700	812	0.65	8310	19390	0.7	27700	0	0	0	0	0	0
Inner gorge MW, natural	0	0	0.00	0	0	0	0	0	0	0	0	0	0
Streamside (non-inner-gorge) MW	1100	32	0.03	330	770	0.7	1100	0	0	0	0	0	0
Road-related MW	1188	35	0.03	356.4	831.6	0.7	0	1188	356.4	831.6	1	1	1
Upland MW	1108	32	0.03	332.4	775.6	0.7	0	1108	332.4	775.6	1	1	1
Road surface erosion	2147	63	0.05	0	2147	1	0	2147	0	2147	1	1	0
Road crossing and gully erosion	7460	219	0.18	2238	5222	0.7	0	7460	746	6714	1	1	0
Skid trail erosion	432	13	0.01	43.2	388.8	0.9	0	432	43.2	388.8	1	1	1
Soil creep	1319	39	0.03	395.7	923.3	0.7	1319	0	0	0	0	0	0
Total	**42454**	**1245**	**1.00**	**11610**	**29525**	**0.70**	**28800**	**12335**	**1478**	**10857**	**0.29**	**0.37**	**0.13**

Tom Long Creek basin, 1966-1981: sediment source analysis results

Sediment Source	Total sediment input, t/yr	Unit-area sediment input (t/km2/yr)	Fraction of total	Coarse sediment input, t/yr	Fine sediment input, t/yr	Fine:total ratio	Natural input, t/yr	Anthropogenic input, t/yr	Anthropogenic coarse input, t/yr	Anthropogenic fine input, t/yr	Anthro: Total sediment input ratio	Anthro: Total fine sediment input ratio	Anthro: Total coarse sediment input ratio
Earthflows toes and associated gullies	27700	812	0.25	8310	19390	0.7	27700	0	0	0	0	0	0
Inner gorge MW, natural	21848	641	0.19	6554	15294	0.7	21848	0	0	0	0	0	0
Streamside (non-inner-gorge) MW	30802	903	0.27	9241	21561	0.7	30802	0	0	0	0	0	0
Road-related MW	1000	29	0.01	300	700	0.7	0	1000	300	700	1	1	1
Upland MW	17197	504	0.15	5159	12038	0.7	0	17197	5159	12038	1	1	1
Road surface erosion	2147	63	0.02	0	2147	1	0	2147	0	2147	1	1	0
Road crossing and gully erosion	7460	219	0.07	2238	5222	0.7	0	7460	746	6714	1	1	0
Skid trail erosion	2889	85	0.03	289	2600	0.9	0	2889	289	2600	1	1	1
Soil creep	1319	39	0.01	396	923	0.7	1319	0	0	0	0	0	0
Total	**112362**	**3295**	**1.00**	**32091**	**78952**	**0.70**	**80350**	**30693**	**6494**	**24199**	**0.27**	**0.31**	**0.20**

Results of Stillwater Sciences' Sediment Source Analysis for the Tom Long Creek Basin
Results of the sediment source analysis for this basin are shown in Table 9 (attached). Shallow landslides contributed a relatively low percentage (9%) to overall sediment loading in the Tom Long Creek basin under recent (1981–1996) conditions. Using 1996 aerial photographs, Stillwater Sciences mapped 33 total shallow landslides in the Tom Long basin (Table 10). The average volume of these 33 features was 960 m^3, or 1,824 t (assuming a bulk density of 1.9 t/m^3). A sediment delivery ratio of 85% was estimated for these landslides, resulting in total delivery of 50,944 t of sediment. Most of the shallow landslides occurred in the Coastal Belt landtype; few were observed in the Melange Matrix.

Stillwater Sciences also mapped active earthflow toes, including some that were not previously mapped by CDMG (1984). Sediment production from earthflow toes and associated gullies is assumed to be natural and was calculated to be the largest sediment source in the basin under current (1981–1996) conditions, accounting for about 65% of total loading. This calculation was based on a total earthflow toe bank length of 1,620 m mapped by Stillwater Sciences in the Tom Long ISA and the average movement rate (1 m/yr) and toe bank height (9 m) assumed for the SFEB (see Section 3.5.2). Mapped active deep-seated features in the Tom Long Creek basin occupy a higher proportion of the landscape in the Melange Matrix (about 15%) than elsewhere in the SFEB (about 5%), accounting for the large contribution of these features to sediment production in the Tom Long basin.

Road crossing and gully erosion was the second largest source of sediment in the Tom Long basin, accounting for about 18% of sediment inputs under recent conditions. Field surveys by Stillwater Sciences of selected roads in the Tom Long basin documented extensive gullying associated with roads and evidence of past crossing failures. Conversations with residents of the basin indicated that many road crossings failed in the early 1980s, likely during the 1982–1983 winter. Although SEDMODL predicts relatively low rates of road surface erosion (2,150 t/yr, or 5% of total erosion in the 1981–1996 period), field observations by Stillwater Sciences indicated that roads are poorly maintained, show evidence of surface lowering, are generally insloped with inside ditches, and likely contribute substantial sheetwash erosion.

Table 10. Summary of landslide mapping in Tom Long Creek basin by Stillwater Sciences, 1981–1996.

Type	Number of Landslides	Total Volume Delivered (m^3)	Total Mass Delivered (t)	Average Delivery for Mapped Area (t/yr)	Land Type Area (km^2)	Average Land Type Unit-Area Delivery ($t/km^2/yr$)	Total Delivery for Whole ISA (34.1 km^2) (t/yr)
Inner gorge natural	0	0	0	0	1.25	0	0
Streamside natural	12	8,687	16,506	1,100	25.75	42.7	1,100
Upland "management"	3	9,375	17,812	1,188	25.75	46.1	1,188
Road-related uplands	18	8750	16,625	1,108	25.75	43.0	1,108
Road-related inner gorge	0	0	0	0	1.25	0	0
Total road-related	18	8750	16,625	1,108	27.00	41.0	1,108
Total	**33**	**26812**	**50,943**	**3,396**	**27.00**	**126**	**3,396**

Analysis of CDMG (1984) mapping of shallow landslides based on 1981 aerial photographs indicated substantially higher sediment loading from shallow landslides in the 1966–1981 period than indicated by our aerial photograph analysis for the 1981–1996 period. CDMG mapped 127 shallow landslides, resulting in sediment production (as estimated by Stillwater Sciences) of about 71,000 t/yr, which constituted about 60% of total sediment (combining inner gorge, streamside non-inner gorge, road-related, and upland slides) during the 1966–1981 period. The difference in landsliding contributions between the 1966–1981 and 1981–1996 periods may be partly related to differences in mapping methods, as it is driven almost entirely by the high rate of shallow landslide production in the earlier period inferred from CDMG maps, although the earlier period was generally wetter with higher sediment yields.

Discussion of Results for Tom Long Creek ISA

Overall, the unit-area sediment input in the 1966–1981 period was substantially higher (3,295 t/km^2/yr) than in the recent period (1,245 t/km^2/yr) in the Tom Long basin. The ratio of anthropogenic to total sediment loading was about the same in both periods, however (0.29 and 0.27). In both periods, total sediment loading was high compared to other ISAs, but the anthropogenic contribution was relatively low. This primarily reflects the effects of natural sediment production from earthflow toes and associated gullies (which we assumed was the same in both periods). The unit-area sediment yield for Melange areas was substantially higher (4,200 t/km^2/yr over an area of 7 km^2 for the 1981–1996 period) than for Coastal Belt areas or for the Tom Long basin as a whole, reflecting the influence of earthflows. This suggests that across the SFEB as a whole, Melange areas likely have substantially higher unit-area sediment yields than Coastal Belt and Yager areas.

As noted above in the discussion of the Hollow Tree ISA results, landslide sediment production values indicated by our analysis of CDMG maps for the 1966–1981 period may be overestimates. The very large difference between landslide sediment production suggested by our mapping results for the recent period (1981–1996) and estimates for 1966–1981 based on CDMG mapping suggests potential error in our assumptions used for conversion of the CDMG mapping into sediment flux, resulting in overall overestimates of sediment loading during the 1966–1981.

Sediment input estimates for the 1966–1981 period in the Tom Long basin can be compared to suspended sediment yield data from Chamise and Dobbyn creeks, which flow into the Eel River near Fort Seward (a short distance east of the Tom Long) and have Melange-dominated geology. These data indicate suspended sediment yields of 3,320 t/km^2/yr in Dobbyn Creek from 1973–1976 and 1,773 t/km^2/yr in Chamise Creek from 1973–1975 (Figure 1; USACE 1980). The Dobbyn Creek results, which include both a very wet year (1974) and a dry year (1976), are almost identical to our estimates of sediment delivery in the Tom Long from 1966 to 1981. The similarity is likely largely coincidental; the Tom Long basin is likely more physiographically similar (and more geographically proximal) to the Chamise Creek basin.

4.2.3 Sproul Creek Basin

The Sproul Creek basin is 62.3 km^2 (24.1 mi^2), accounting for about 3.5% of the SFE drainage area. Sproul Creek flows into the South Fork Eel River from the west near the town of Garberville (Maps 1, 7). Mean annual precipitation in the Sproul Creek basin is between 150 and 200 cm (60 and 80 inches) (James 1983). The Sproul Creek basin is underlain by rocks of the Coastal Belt Franciscan and Yager Formation. These geologic units are described in more detail in Section 2.1. Sproul Creek is considered representative of the

Coastal Belt geomorphic terrain in our analysis, despite the presence of Yager Formation lithology, because the topography, precipitation levels, and seismic activity in the Sproul Creek basin (secondary criteria used in our stratification of the SFEB into geomorphic terrains) are more characteristic of those portions of the SFEB with predominantly Coastal Belt lithology than with predominantly Yager lithology (Maps 3, 4). According to the SHALSTAB model, 2.1% of the land in the Sproul Creek basin is in high and chronic instability classes, compared to about 3.8% for the SFEB as a whole (Table 5).

Sixty-five percent of the Sproul Creek basin is owned by Barnum Timber Company. The rest of the land in the basin is owned by Wagner Timber Company (mainly in Little Sproul and Warden Creek basins) and by smaller private landowners (6.1 km^2 [1,500 ac] in the southeast portion of the Sproul Creek basin, which includes some grassland areas) (Wooldridge 1991). A CDFG report indicated that Sproul Creek is one of the best chinook salmon spawning streams in the SFEB and possibly in the whole Eel River basin (McLeod and Preston 1990). USBLM et al. (1996, p. 28) lists Sproul Creek as an important coho salmon stream with “relatively good” habitat.

Land Use History in Sproul Creek Basin

Timber harvesting in the Sproul Creek basin began in the 1940s after World War II, and most old-growth conifers had been harvested by the early 1960s. Logging practices were typical of the period, with skid trails frequently running up streams, tractor yarding, and harvest mostly by clearcutting (Wooldridge 1991). Logging from the 1940s to the 1960s converted vegetation dominated by large, old-growth conifers to second-growth conifers, hardwoods, and brush (Platts 1991). Very little harvest activity occurred from the early 1960s through the early 1980s on Barnum Timber Company lands (Wooldridge 1991). Since the mid-1980s, logging of hardwoods and second-growth conifers has occurred, including clearcutting stands with a high volume of hardwoods (Wooldridge 1991).

Platts (1991) assessed aerial photographs of the Sproul Creek basin from 1941 to 1988, documenting general changes in land use, vegetation cover, and erosional patterns. In the 1941 photographs, little evidence of anthropogenic activities was visible, a closed canopy of old-growth redwood and Douglas-fir covered mainstem Sproul Creek and its valley bottom, and no sediment fan was observed at the mouth of Sproul Creek where it joins the SFE. The 1947 photographs document that a valley-bottom road had been built along Sproul Creek from its mouth up to 1.6 km (1 mi) below the West Fork Sproul Creek confluence, and the areas adjacent to this valley-bottom road had been logged, eliminating the coniferous canopy over the channel. Upslope areas along Sproul Creek and areas upstream of the West Fork Sproul Creek confluence remained undisturbed in 1947.

Analysis of 1954 photographs by Platts (1991) showed that the valley-bottom road along Sproul Creek had been extended to the headwaters of the basin, hillslopes adjacent to Sproul Creek had been extensively logged, and skid trails, including in streams, were widespread. As in the 1941 and 1947 photographs, no sediment fan was visible at the mouth of Sproul Creek. Aerial photographs from 1963 showed evidence of extensive road and hillslope erosion, further timber harvesting in upslope areas, enlargement of stream channels, and a large sediment fan at the mouth of Sproul Creek. Wooldridge (1991) indicated that deposition of sediment by the 1964 flood caused aggradation of approximately 11 m (35 ft) at the confluence of Sproul Creek and the SFE and of about 1.5–3.0 m (5–10 ft) in upstream reaches of mainstem Sproul Creek and West Fork Sproul Creek. Aerial photographs from 1974 indicated that upland slopes had revegetated and stabilized, although the Sproul Creek channel appeared to remain unstable and riparian vegetation was absent (Platts 1991). The sediment fan at the mouth of Sproul Creek was substantially larger on 1974 photographs than on the 1963 photographs, likely reflecting the effects of the 1964 flood and ongoing high sediment loads. As of 1981, Sproul Creek still lacked riparian vegetation, appeared unstable, and was widened compared to pre-land management conditions, although the sediment fan at the mouth was smaller than in 1974 photographs (and slightly larger than in 1963 photographs) (Platts 1991). As of 1988, the stream appeared to be recovering, with alder riparian vegetation establishing but riparian conifers remaining small or absent (Platts 1991).

As noted above, recent and ongoing land uses have been characterized by logging of hardwoods and second-growth conifers since the mid-1980s (Wooldridge 1991). Current harvest practices by Barnum Timber Company are intended to convert stands currently dominated by hardwoods that regenerated following logging of old-growth conifers into mixed conifer forests (Wooldridge 1991). Clearcutting with cable yarding and replanting of conifers following harvest are used (Wooldridge 1991). From 1986 to 1988, 1000–2000 ac/yr (4.0–8.1 km^2/yr) were thinned (Wooldridge 1991), and as of 1991, 200 ac/yr (0.8 km^2/yr) were clearcut and an additional 50–100 ac (0.2–0.4 km^2) were thinned, with plans calling for continuing this rate after 1991 (Wooldridge 1991).

Total road density in Sproul Creek is currently about 3.22 km/km^2 (5.2 mi/mi^2), based on road coverages obtained from Barnum Timber Company and CDF/FRAP. This may be an underestimate, because old, abandoned roads may not be adequately accounted for. The CDF/FRAP coverage indicates a total road length of 243.5 km in the basin, and the Barnum Timber Company coverage indicates a road length of 200.7 km in the Barnum ownership. Many of these are valley-bottom roads adjacent to stream channels. Road maintenance efforts have included outsloping, surfacing with gravel/rock, and placing straw in ditchlines to reduce sediment delivery (Wooldridge 1991).

CDFG has implemented a number of restoration projects in the Sproul Creek basin in an effort to improve fish habitat, some of which may have had unintended negative consequences. As early as 1949, CDFG began removing large woody debris (LWD) from Sproul Creek and its tributaries, a practice that continued at least through about 1990 (Platts 1991). CDFG has also attempted to stabilize landslides, modified natural barriers in streams, and installed weirs (McLeod and Preston 1990).

Previous Studies of Erosional Processes in Sproul Creek
Based on bulk (McNeil) samples of gravel quality at four stations (lower mainstem Sproul Creek below West Fork Sproul Creek, upper mainstem Sproul Creek, upper West Fork Sproul Creek, lower West Fork Sproul Creek below LaDoo Creek, McLeod and Preston (1990) concluded that the percent of fine sediment in spawning gravels was at a deleterious level for egg and alevin survival. Their samples showed a range of 16.2–31.9% fines $\leq$0.85 mm; with the means of four stations ranging from about 22–26%. McLeod and Preston (1990) also suggested that rearing habitat of pools that they sampled had been reduced by at least 24–26% by sediment filling. Based on these measurements, McLeod and Preston (1990) concluded that Sproul Creek was "heavily impacted by sedimentation. Future timber harvest activities should be conducted in such a way that there is no net increase in discharge of sediments to the stream system (p. 3)." In response to this finding, Barnum Timber Company commissioned studies of erosional processes and channel conditions in the Sproul Creek basin (Platts 1991, Rice 1991, Wooldridge 1991), which are summarized below. These studies dispute the methodology used by MacLeod and Preston (1990) and suggest that their fine sediment measurements were influenced by a lack of large peak flows in the years preceding the measurements (Platts 1991, Rice 1991).

Rice (1991) assessed erosional processes in the Sproul Creek basin using field surveys in July 1991 and data from his Critical Sites Erosion Study (CSES), in which he sampled road and harvest area plots throughout northwestern California and developed a method for predicting erosion risks (Lewis and Rice 1990, Rice and Lewis 1991). Based on field surveys in Sproul Creek, Rice (1991) estimated a road erosion rate for Barnum Timber Company roads of 5,760 m^3/km^2 (30.47 yd^3/ac) over an undefined time period. This applies to three types of roads: (1) secondary roads built from 1976 to 1982, most of which are midslope roads; (2) new roads built since 1986, most of which are short midslope roads connecting existing roads; and (3) existing seasonal roads reconstructed since 1986. In addition, random sampling on public utilities roads in La Doo Creek suggested that substantial sediment production occurs from this type of roads. Rice did not estimate sediment production from streamside haul roads built in the post-WWII era, although many such roads occur in the Sproul Creek basin (Map 7). Rice also concluded that harvest-area erosion rates were substantially lower in Sproul Creek than for harvest-area sites surveyed by Rice as part of the CSES, and that harvest areas yielded 16% of the total erosion he estimated in the Sproul Creek basin.

Wooldridge (1991) applied results from the USDA (1970) report on sediment yield in the Eel and Mad river basins from 1942 to 1965 (see Section 4.3 below for further discussion of the USDA report) to estimate sediment yield in Sproul Creek and the contribution of timber harvest activities on Barnum Timber Company land. Rice (1991) and Wooldridge (1991) both concluded that harvest activities on Barnum Timber Company lands occurring at the time of their reports had a limited influence on sediment yield in Sproul Creek. The sediment source analysis by Stillwater Sciences for the Sproul Creek basin developed different conclusions, finding that anthropogenic contributions to total sediment flux have generally been high, as presented in the following section.

Results of Stillwater Sciences' Sediment Source Analysis for the Sproul Creek Basin

Stillwater Sciences estimated sediment production in the Sproul Creek basin based on the methods described in Section 3.4 and 3.5, and results are presented below. For the Sproul Creek basin, mapping of 1994 aerial photographs (provided by Barnum Timber Company) was used to assess current conditions. Because mapping was based on 1994 photographs, the "current conditions" period is assumed to refer to 1981–1994, rather than extending to 1996 as with the other ISAs. The year 1981 was used to bracket the beginning of the "current conditions" period, as with other ISAs, because only landslides not mapped by CDMG (1984) from 1981 aerial photographs were mapped by Stillwater. Aerial photographs were available for a 50.4 km^2 area, or 81% of the total Sproul Creek basin area of 62.3 km^2. The mapped area corresponded to Barnum Timber Company ownership and adjacent areas. Barnum Timber Company also provided access to its GIS roads coverage. Stillwater Sciences did not conduct field surveys in Sproul Creek due to time constraints. The sediment source assessment for the Sproul Creek basin was therefore based entirely on remote methods. Stillwater Sciences mapped an area of large inner gorges of 3.75 km^2 in the Sproul Creek basin.

Results of the sediment source assessment for the Sproul Creek basin are summarized in Table 11 (attached). For the "current conditions" assessment, Stillwater Sciences mapped a total of 61 shallow landslides in the Sproul Creek basin on 1994 aerial photographs, as summarized in Table 12. The mapped shallow landslides mobilized an estimated total of 178,990 tons of sediment, with an estimated 163,845 tons delivered to streams, resulting in an overall estimated delivery ratio of 92%. The unit-area sediment

Table 11.

Sproul Creek basin, 1981-1994: sediment source analysis results

Sediment Source	Total sediment input, t/yr	Unit-area sediment input (t/km2/yr)	Fraction of total	Coarse sediment input, t/yr	Fine sediment input, t/yr	Fine:total ratio	Natural input, t/yr	Anthropogenic input, t/yr	Anthropogenic coarse input, t/yr	Anthropogenic fine input, t/yr	Anthro: Total sediment input ratio	Anthro: Total fine sediment input ratio	Anthro: Total coarse sediment input ratio
Earthflows toes and associated gullies	0	0	0.00	0	0	0	0	0	0	0	0	0	0
Inner gorge MW, natural	5029	81	0.15	1508.7	3520.3	0.7	5029	0	0	0	0	0	0
Streamside (non-inner-gorge) MW	2742	44	0.08	822.6	1919.4	0.7	2742	0	0	0	0	0	0
Road-related MW	2289	37	0.07	686.7	1602.3	0.7	0	2289	686.7	1602.3	1	1	1
Upland MW	4203	67	0.12	1260.9	2942.1	0.7	0	4203	1260.9	2942.1	1	1	1
Road surface erosion	2189	35	0.06	0	2189	1	0	2189	0	2189	1	1	0
Road crossing and gully erosion	16470	264	0.48	4941	11529	0.7	0	16470	1647	14823	1	1	0
Skid trail erosion	987	16	0.03	98.7	888.3	0.9	0	987	98.7	888.3	1	1	1
Soil creep	500	8	0.01	150	350	0.7	500	0	0	0	0	0	0
Total	**34409**	**552**	**1**	**9469**	**24940**	**0.72**	**8271**	**26138**	**3693**	**22445**	**0.76**	**0.90**	**0.39**
Unit area total, $t/km^2/yr$	**552**												
	17939							9668			**0.54**		

Sproul Creek basin, 1966-1981: sediment source analysis results

Sediment Source	Total sediment input, t/yr	Unit-area sediment input (t/km2/yr)	Fraction of total	Coarse sediment input, t/yr	Fine sediment input, t/yr	Fine:total ratio	Natural input, t/yr	Anthropogenic input, t/yr	Anthropogenic coarse input, t/yr	Anthropogenic fine input, t/yr	Anthro: Total sediment input ratio	Anthro: Total fine sediment input ratio	Anthro: Total coarse sediment input ratio
Earthflows toes and associated gullies	0	0	0.00	0	0	0	0	0	0	0	0	0	0
Inner gorge MW, natural	17882	287	0.33	5365	12517	0.7	17882	0	0	0	0	0	0
Streamside (non-inner-gorge) MW	8050	129	0.15	2415	5635	0.7	8050	0	0	0	0	0	0
Road-related MW	1133	18	0.02	340	793	0.7	0	1133	340	793	1	1	1
Upland MW	1133	18	0.02	340	793	0.7	0	1133	340	793	1	1	1
Road surface erosion	2189	35	0.04	0	2189	1	0	2189	0	2189	1	1	0
Road crossing and gully erosion	16470	264	0.31	4941	11529	0.7	0	16470	1647	14823	1	1	0
Skid trail erosion	6602	106	0.12	660	5942	0.9	0	6602	660	5942	1	1	1
Soil creep	500	8	0.01	150	350	0.7	500	0	0	0	0	0	0
Total	**53959**	**866**	**1.00**	**14211**	**39748**	**0.74**	**26432**	**27527**	**2987**	**24540**	**0.51**	**0.62**	**0.21**

production estimated for shallow landslides in the mapped area (50.4 km^2) was extrapolated to unmapped portions of the Sproul Creek basin (differentiated into inner gorge vs. non-inner-gorge areas) to develop sediment delivery estimates for the whole Sproul Creek basin (Table 12). This suggests total sediment delivery of 14,263 t/yr from landslides in the Sproul Creek basin.

No active earthflows were mapped in the Sproul Creek basin, resulting in zero sediment delivery from this source. Sediment inputs from road surface erosion were estimated at 2,189 t/yr (35 t/km^2/yr) using SEDMODL. This includes a road prism sheetwash delivery ratio of 8.6% (i.e., 8.6% of total road length directly delivers sediment to stream channels), which may be an underestimate given the presence of streamside roads. Soil creep was also estimated using SEDMODL, which indicated chronic sediment input from creep of about 500 t/yr. This value is based on a channel length of 124 km bordering slopes with gradients less than 30%, producing 318 t/yr, and 35 km bordering slopes greater than 30%, producing 182 t/yr. Channel lengths and hillslope gradients were determined by the Stillwater Sciences 10-m DEM and channel network.

A large amount (16,500 t/yr) of sediment delivery was estimated for road crossing and gully erosion (based on methods described in Section 3.5.4), reflecting the high road density in the Sproul Creek basin and the sensitivity to road density of our method for assessing this sediment source. These results are based on extrapolation of unit-road length rates of road crossing and gully erosion from the Hollow Tree, Tom Long, and Bull Creek ISAs, rather than on road erosion data from the Sproul Creek basin, however, and many roads in Sproul Creek are upslope roads that likely have relatively low delivery ratios to streams. In addition, brief field observations by Stillwater Sciences in the Sproul Creek basin (on Barnum Timber Company lands) indicated that road maintenance practices are good, with many roads being outsloped with rocked surfaces. Road construction and maintenance practices therefore likely reduce crossing and gully erosion below the rates predicted here. Additional field surveys would be required to more accurately quantify road crossing and gully erosion in the Sproul Creek basin.

Table 12. Summary of landslide mapping in Sproul Creek basin by Stillwater Sciences, 1981–1994.

Type	Number of Landslides	Total Volume Delivered (m^3)	Total Mass Delivered (t)	Average Delivery for Mapped Area (t/yr)	Land Type Area (km^2)	Average Land Type Unit-Area Delivery (t/km^2/yr)	Total Delivery for Whole ISA (62.3 km^2) (t/yr)
Inner gorge natural	17	34,406	65,372	5,029	3.75	1,341	5,029
Streamside natural	21	14,906	28,322	2,179	46.05	47.3	2,742
Upland “management”	11	22,860	43,434	3,340	46.05	72.5	4,203
Road-related uplands	9	6,187	11,756	904	46.05	19.6	1,138
Road-related inner gorge	3	7,875	14,963	1,151	3.75	307	1,151
Total road-related	12	14,062	26,718	2,055	49.8	41.3	2,289
Total	**61**	**86,234**	**163,845**	**12,603**	**49.8**	**253**	**14,263**

For the 1966–1981 period, 129 debris slides were shown on CDMG maps for the entire Sproul Creek basin (62.3 km^2), including 106 point slides and 23 active debris slides. The largest number of landslides were in inner gorges (48 total, including 33 point slides and 15 active debris slides), resulting in sediment production of 17,882 t/yr or 287 t/km^2 /yr (over 62.3 km^2). A total of 47 landslides were judged to be non-inner-gorge, natural streamside features, including 39 point slides and 8 active debris slides, resulting in delivery of 8,050 t/yr. The number of road-related and "upland management" landslides was low (17 each).

Discussion of Results for Sproul Creek ISA
The sediment source assessments indicate that average sediment loading was higher (866 t/km^2/yr) in the 1966–1981 period than in the 1981–1994 period (552 t/km^2/yr). The ratio of anthropogenic to total inputs was higher in the recent period (0.76) than in the 1966–1981 period (0.51), when natural inner gorge landslides represented the largest sediment source. This result may reflect the increase in timber harvest activities in the 1981–1994 period compared to the 1966–1981 period and reduced natural sediment production because of drier climatic conditions. The high anthropogenic contribution in the recent period is largely a function of the large amount of sediment production assigned to road crossing and gully erosion and therefore may be overestimated, as discussed above (about 63% of the anthropogenic contribution is from road crossing and gully erosion; if this source were assumed to equal zero, the overall anthropogenic:total ratio would be 0.54). In both periods, the unit-area sediment delivery was lower in this basin than in other ISAs. This difference is partly attributable to the absence of active earthflows in the Sproul Creek basin. Our analysis suggests higher sediment loading from anthropogenic activities than indicated by previous studies in the Sproul Creek basin (Wooldridge 1991, Rice 1991).

4.2.4 Bull Creek Basin

The Bull Creek basin is representative of the Yager terrain, high precipitation and uplift rates, and of a land-use pattern characterized by substantial impacts followed by a "recovery" period. The Bull Creek basin has an area of 112 km^2 (43.3 mi^2) (Stillwater Sciences GIS) and is currently within Humboldt Redwoods State Park. The basin is in the northwest portion of the SFEB, and Bull Creek enters the South Fork Eel River near its confluence with the Eel River (Maps 1, 9).

Compared to other areas in the SFEB, a substantial amount of existing data on sediment sources is available for the Bull Creek basin. Sediment source assessments have been completed for two subbasins in the Bull Creek watershed: Cuneo Creek, a 10 km^2 (3.9 mi^2) drainage entering Bull Creek from the northwest (Short 1993), and Preacher Gulch, a 2.6 km^2 (1 mi^2) basin in the upper Bull Creek watershed on the western slopes of Grasshopper Peak (Fiori et al. 1999). In addition, a series of reports by LaVen and various co-authors contributed to a basin-wide study of erosion and sedimentation problems in Bull Creek carried out from 1980 to 1986 (Horns and LaVen 1986, LaVen 1984, 1987a). This included development of a "synthetic" sediment budget for the Bull Creek basin based on existing data (LaVen 1987a). Because of the availability of existing studies on geomorphic processes in the Bull Creek basin, we did not complete a sediment source assessment similar to those for the other ISAs (based on aerial photograph mapping and resulting in production estimates for each of the source categories delineated in Section 3.5). Instead, Stillwater Sciences analyzed the results of existing studies in order to provide insight into sediment sources in the Bull Creek basin. Because comparable methods were not used, Bull Creek is not an ISA in the same sense as the Hollow Tree, Tom Long, and Sproul ISAs, and Bull Creek results were not used for extrapolation to the rest of the SFEB. Discussion of Bull Creek is included here, however, because of the previous work done there and the insight Bull Creek provides into the large magnitude of spatial variability of sediment loading in the SFEB.

Physiographic Conditions

For the purposes of this analysis, Bull Creek was considered characteristic of the Yager terrain, which underlies most of the basin and Humboldt Redwoods State Park (Fiori et al. 1999), although a sheared contact zone between the Coastal Belt and Yager terrains occurs in the basin. The Bull Creek basin is tectonically and seismically active, with high uplift rates, numerous faults, proximity to the Mendocino Triple Junction, and substantial shearing and faulting, all of which likely have a strong influence on landsliding and other geomorphic processes (Fiori et al. 1999, Horns and LaVen 1986). In general, seismically induced groundshaking and ground breakage (surface cracks, changes in subsurface flow patterns, ridge-top depressions) may be factors in high sediment production (Fiori et al. 1999). Fiori et al. (1999) mapped numerous landslides where roads concentrated runoff onto areas with previously unmapped faults. The Garberville fault zone likely underlies a portion of the upper Bull Creek basin and has a strong structural and geomorphic influence in this area (Kelsey and Carver 1988, as cited in Fiori et al. 1999).

In addition, the Bull Creek basin has high precipitation levels, with rainfall averaging 152–292 cm/yr (60–115 in/yr) in different parts of the basin; the upper end of this range represents the highest rainfall in the SFEB. Grasshopper Mountain has a strong orographic effect, creating very high rainfall rates in areas such as the upper Preacher Gulch subbasin (Fiori et al. 1999). The combination of high precipation, weak bedrock, and high uplift rates contribute to hillslope instability, high rates of downcutting (channel incision) and high natural sediment yields in the Bull Creek basin (LaVen 1984a, Horns and LaVen 1986).

Land Use History

The land use history of the Bull Creek basin has been well documented (e.g., Gilligan 1966), and land use patterns in the basin in the period before state ownership were likely similar to other areas in the Yager and Coastal Belt terrains. A lack of access limited logging in the Bull Creek basin before WWII (Gilligan 1966), although small-scale logging did occur in the basin from the late 1800s to the 1940s (Jager and LaVen 1981). These activities had “negligible impact on either the redwood forests of the lower Bull Creek drainages or on the Douglas-fir forests of the upper basin” (Gilligan 1966). In the upper Bull Creek basin, grazing (mostly cattle, some sheep) was the major land use until the early 1940s, with periodic burning to maintain open grasslands for grazing.

After WWII, logging activity accelerated rapidly in the Bull Creek basin, promoted in part by taxation of standing old-growth trees starting in 1946 and by increased demand for Douglas-fir (Gilligan 1966). A timber tax stipulated that landowners were required to remove at least 70% of timber volume from their property in order to avoid taxation (Fiori et al. 1999). By 1954, 50% of the upper Bull Creek basin had been logged, and by 1960, 85% of the upper Bull Creek basin (60% of the entire watershed) had been cut (Jager and LaVen 1981). In the Cuneo Creek basin, all merchantable timber had been logged by the late 1960s, after which the Cuneo Creek basin was purchased by the state (Short 1987). Standard logging methods of that period were used, including clearcutting, tractor logging, construction of dense road and skid trail networks, substantial exposure of bare soil, and an absence of erosion control measures (Gilligan 1966, Jager and LaVen 1981, Short 1987). Range-burning practices on forests and grasslands also continued after WWII. Between 1950 and 1959, 8 fires larger than 100 acres burned more than 8,700 acres in the basin, in addition to many smaller fires. About 50% of the upper basin was burned in this period, including areas burned for converting forests to grazing land (Gilligan 1966). These practices likely contributed to sediment delivery by increasing the amount of bare ground.

Aerial photograph analysis of the Preacher Gulch subbasin (Fiori et al. 1999) provides insight into land use history and geomorphic effects in the upper Bull Creek basin. On 1942 photographs, inner gorge areas and stream channels were covered by intact riparian forest and generally appeared stable; no active landslides were visible. Land uses during the period represented by 1942 photographs included ranching (ranch access roads, which primarily occurred on ridgetops, were visible on photographs and appeared "generally geomorphically benign") and tanbarking, which likely caused "little sediment production" compared to later activities (Fiori et al. 1999). Photographs from 1954 indicated that logging and burning had eliminated most vegetation and exposed substantial bare ground in the lower portion of the Preacher Gulch subbasin and a dense skid trail network had been built on steep slopes and in stream channels. No major gullies or debris slides were visible on denuded areas in 1954, however (Fiori et al. 1999). Logging extended into the upper Preacher Gulch subbasin from 1955–1966, including additional road and skid trail construction, road and crossing failures in 1955 and 1964, severe gullying of road treads and small landslides (<1000 m^3) related to road diversions, and removal of most riparian and upslope vegetation (Fiori et al. 1999).

Storm/Flood History

Substantial erosion and changes to channel morphology occurred during the December 1955 storm and flood event in the Bull Creek basin, which appears to have represented the first major geomorphic response to land use in the Bull Creek basin (Merrill and Vadurro 1999, Fiori et al. 1999). During this storm, 44.8 cm (17.6 in) of rainfall fell over a 5-day period (Gleason 1956), resulting in an estimatated peak flow of about 16,000 cfs in Bull Creek at its confluence with the SFE (Jager and LaVen 1981). This is the largest event on record in Bull Creek and was exacerbated by the collapse of a log jam that released a large surge of water and debris (Gilligan 1966). The flood entrained large amounts of anthropogenic debris, large redwoods, and sediment, depositing them in the lower 6 miles (9.7 km) of Bull Creek (Jager and LaVen 1981) and burying the townsite of Bull Creek in gravel and debris. The county highway bridge over Cuneo Creek was also buried by gravel during this event. Following recession of the 1955 flood, clearance and burning of debris from channels was initiated (Jager and LaVen 1981).

The December 1964 flood, which was the largest on record elsewhere in the SFEB, was the third-largest event in the Bull Creek basin, with a peak discharge of 6520 cfs. This event triggered inner gorge and upslope landsliding in the upper Bull Creek basin (Fiori et al. 1999), deposited up to 30 ft (9.15 m) of sand/silt/gravel in upper reaches of Bull Creek and Cuneo Creek, and buried a second bridge over Cuneo Creek (Jager and LaVen 1981). The 1964 flood resulted in widening of Bull Creek by up to 400 ft (122 m) in some locations, raising of the channel bed by 4–6 feet (1.2–1.8 m), and formation of a large alluvial delta at the SFE confluence. In addition, over 850 old-growth redwoods were felled by bank erosion (Jager and LaVen 1981).

Erosional impacts associated with the 1955 and 1964 events contributed to efforts to acquire uplands areas in order to provide long-term protection for old-growth redwoods in the lower Bull Creek basin. By 1966, much of the basin (all except 3000 acres) had been incorporated into state parks ownership; nearly 15,000 acres were acquired between 1962 and 1966 (Gilligan 1966). Various efforts to control sediment movement and bank erosion have been implemented since the 1955 flood, including construction of sediment retention dams, riprapping of the lower mainstem, and channel clearing and shaping (Jager and LaVen 1981).

The second largest discharge of record in Bull Creek occurred on January 1, 1997, when a flow of 7,830 cfs was recorded at the Bull Creek near Weott gauge. This event was preceded by almost 50 inches (127 cm) of rain in December 1996 (recorded at a gage near Cuneo Creek), including nearly 30 inches (76.2 cm) during a 9-day storm leading up to the flood. This event "triggered widespread slope failure throughout Preacher Gulch, including reactivation of previously dormant landslides and retrogression and lateral expansion of inner gorge failures that had initiated during the 1955 and 1964 storms" (Fiori et al. 1999). A landslide-triggering storm also occurred in December 1995, causing mass wasting and sediment delivery in the upper Bull Creek basin (Merrill and Vadurro 1999). Landslides during the 1996–1997 winter (and during 1995) may have been influenced by slope adjustments following earthquakes in 1991 and 1992 that occurred within about 10 miles (16.1 km) of the Bull Creek basin (Fiori et al. 1999).

During the 1997–1998 El Niño winter, precipitation in Bull Creek was 150% of normal levels. Because of the temporal pattern of precipitation, which was marked by several moderate storms with short dry intervals, substantial slope failures were not triggered as in the 1996–1997 winter (Fiori et al. 1999). El Niño stream flows appeared to incise through deposits of previous year in Bull Creek (Merrill and Vadurro 1999).

Merrill and Vadurro (1999) examined annual hydrographs from the Bull Creek near Weott gage from 1961 to the present (the period of record at this gage) in order to assess potential effects of revegetation, but they found no significant change in the pattern or magnitude of runoff.

Past Studies of Sediment Sources in the Bull Creek Basin

An early study of erosion issues in the Bull Creek basin was carried out by Gleason (1956), who documented impacts from the 1955 flood and post-WWII logging. Gleason noted that logged areas produced overland flow and that runoff concentrated on roads and skid trails lacking drainage structures caused formation of large gullies and delivered large amounts of sediment to channels. In contrast, he observed only a small degree of slumps and gullies in grassland areas, suggesting that grazing had not contributed to erosional and flooding impacts.

Preacher Gulch Subbasin

The most recent and detailed sediment source assessment carried out in the Bull Creek basin is provided by Fiori et al. (1999), who completed a sediment source assessment for Preacher Gulch, a small (1.0 mi^2) (2.6 km^2) subbasin in the upper Bull Creek basin. Their analysis was part of erosion control efforts in the upper Bull Creek basin that included decommissioning of 2.9 miles (4.7 km) of road and erosion control on 218 ac of land affected by gullies and landslides. The material that follows is summarized from Fiori et al. (1999). The results of their study may be applicable, in a broad sense, to other areas in the upper Bull Creek basin.

A combination of factors contribute to high sediment production rates in the Preacher Gulch subbasin, including the tectonic setting (Preacher Gulch is 10 miles (16.1 km) east of the Mendocino Triple Junction), high precipitation levels, and effects of past land uses, particularly in terms of stream diversions. Preacher Gulch was intensively logged from 1947–1966 and was purchased by the state in the mid-1960s. Preacher Gulch is characterized by Hugo series soils (35% is coarse, >2 mm) in 80% of the basin; an additional 14% (including grasslands) has Laughlin series soils. Large dormant deep-seated landslides underlie much of the landscape (averaging 12 ac in size).

Fiori et al. (1999) identified the following mechanisms, in order of importance, as those that are currently responsible for most sediment delivery in the Preacher Gulch subbasin: (1) road-related flow diversion onto unstable hillslope areas; (2) gullying on steep hillslopes; (3) stream crossing failures; (4) fillslope and cutslope failures; and (5) road surface erosion. Fiori et al. (1999) indicate that regeneration of vegetation and development of duff/litter accumulations have reduced surface erosion, with road failures and mass wasting having increased in importance as sediment delivery mechanisms. Their results, as described in further detail below, provide strong evidence of the legacy effects of old roads on sediment production, since the roads in the Preacher Gulch subbasin were built in the 1940s to 1960s and have received little use since then.

Fiori et al. (1999) based their sediment source assessment on aerial photograph analysis (1942, 1954, 1956, 1960, 1966, and 1997 photographs) and comprehensive field mapping in winter/spring 1997. This included classification of the road and skid-trail network (including crossings, runoff diversions, and gullies) and active erosion features, and assessment of potential natural and anthropogenic sediment delivery to streams. A landslide inventory was developed, including estimates of activity level, depth, volume and delivery ratios. The authors suggested that this inventory likely resulted in minimum estimates of landslide sediment production, because depth estimates were conservative on the shallow side and the inventory focused on larger debris slides and torrents. Erosion from smaller slides, inner gorge failures, and streambank erosion was underrepresented, according to Fiori et al. (1999).

Based on this inventory, a total of 33 mass wasting features were quantified in the Preacher Gulch basin; these contributed a minimum of 154,601 yd^3 (118,208 m^3) to channels between 1954 and 1997 (about 2,017 $t/km^2/yr$, assuming a 43-yr period and a bulk density of 1.9 t/m^3). Most of this sediment was delivered by a small number of deep-seated landslides (>15 ft [4.6 m] depth). Shallow debris flows, debris torrents, gullies, and inner gorge failures also delivered sediment. More than one-third of the 1954–1997 sediment yield (36%) was from landslides originating on the lower Preacher Gulch Road (or associated with drainage from this road); nearly half of this delivery (26,841 yd^3 [20,523 m^3]) occurred in 1997. Nearly all significant landslides documented in Preacher Gulch in 1997 were road-related.

Fiori et al. (1999) indicated that yield from shallow inner gorge failures and surface erosion appeared to be declining, probably because of recovery of riparian and hillslope vegetation. On the other hand, they noted that "in light of the large volume of landslide sediment delivery in 1997 (compared to the total volume delivered since 1954) it appears reasonable to assume that rates of anthropogenically influenced sediment delivery had not begun to decline in the Preacher Gulch watershed [by that time]."

Sediment delivery from gullies and surface erosion was not quantified, although field observations suggested that at least one foot of sheetflow erosion has occurred since the early 1960s. Using Reid and Dunne's (1984) methods, Fiori et al. (1999) suggested a rate of surface erosion from the lower Preacher Gulch road in recent years, when the road has received light use for Park maintenance, of 9 yd^3/yr (6.9 m^3/yr). This rate is small compared to landslide sediment delivery; sediment yield from landslides in 1997 related to the lower Preacher Gulch road was estimated to be approximately 2,500 times greater than the average yearly road surface erosion for the same road section. The rate of surface erosion on abandoned roads is "very minor" (0–1 yd^3/yr [0–0.8 m^3/yr]) due to revegetation of their surfaces. Active system roads have a density of 4.5 mi/mi^2 (2.8 km/km^2) in Preacher Gulch, while abandoned roads have a density of 17.7 mi/mi^2 (11 km/km^2), resulting in a total road density 22.2 mi/mi^2 (13.8 km/km^2). This road density is substantially higher than the road densities for ISAs reported in Table 4 above, suggesting that road densities in these areas may be underestimated because of underrepresentation of abandoned roads.

Fiori et al. developed unit-area sediment yields for roads, providing rough approximations of future sediment production rates, assuming an absence of rehabilitation efforts and similar frequency of future triggering events (e.g., fire, earthquake, storm). Based on delivery of about 56,245 yd^3 (43,005 m^3) of sediment from 1954–1997 for the lower 2.6 km (1.6 miles) of the Preacher Gulch road and an average road width of 6.7 m (22 ft), this indicates a sediment delivery rate of 0.007 $yd^3/yr/ft^2$ of road (0.058 $m^3/yr/m^2$) (56,245 yd^3/43 yr/[1.6 mi * 5,280 ft/mi] * 22 ft); which applies to "cross-faulted roads on or near the upper third of the inner gorge slope with an average side slope of about 55% grade" (Fiori et al. 1999, p. 47).

Cuneo Creek Subbasin

A sediment source analysis has also been developed for the Cuneo Creek subbasin (Short 1993), which is believed to have one of the highest sediment yields of any tributary to Bull Creek. This subbasin has an area of 10 km^2 and is located in a zone of high tectonic uplift and pervasive shearing; a fault may also pass through this subbasin. The results of Short's (1993) sediment budget for Cuneo Creek are summarized below. The Cuneo Creek sediment budget was constructed for the period from 1950 to 1986; it included aerial photograph and field mapping of landslides and earthflows and application of Redwood Creek study results to estimate sediment production from gullies, sediment yield estimates based on one winter of suspended sediment sampling, and channel-sediment storage estimates based on mass balance and cross-sections (Short 1993).

Channel morphology in lower Cuneo Creek has changed substantially in response to large flood events and increased sediment inputs. Channel width increased from 10s to 100s of meters, becoming widest following the 1964 flood, which resulted in complete channel filling and destruction of riparian vegetation (Short 1987). Bridges built over Cuneo Creek near its mouth were buried in both the 1955 and 1964 floods, suggesting that up to 12 m of aggradation occurred (Short 1987).

Short (1993) estimated that between 1950 (approximately when timber harvesting began) and 1986, total hillslope erosion was 6.226 million t in the Cuneo Creek basin (which corresponds to a unit-area rate of 16,827 $t/km^2/yr$, assuming a 37-year time period). Landslides accounted for 87% of the total (5.4 million t), gullies accounted for 7% (454,000 t), and earthflows accounted for 6% (372,000 t) of total hillslope erosion (other sources were not considered). Hillslope erosion from landslides was estimated by aerial photograph mapping of landslides, with a subset of landslides measured in the field for dimensions; volumes of landslides were calculated and summed to get total landslide yield since 1950. Of the total landslide volume for 1950–1986, 27% (0.76 million m^3 [1.45 million t]) was from a single slide, the Devil's Elbow slide. Gully erosion was not directly measured; estimates were developed based on Redwood Creek studies (Weaver et al. in press [i.e., Weaver et al. 1995]). Sediment production from earthflows was also estimated using data from Redwood Creek on average rates of earthflow movement (assumed average of 0.21 m/yr) and aerial photograph mapping of earthflows in the Cuneo Creek basin. Short did not assess the relative contribution of anthropogenic activities to hillslope erosion.

Short (1993) estimated sediment discharge from the basin based on synoptic sampling from October 1985 to February 1986. The 1985–1986 suspended sediment data were applied to a range of flows in order to calculate sediment yield for the 1950–1986 period. This method assumed that the sediment to discharge relationship remained constant during the 1950–1986 period and indicated an estimated sediment yield of 275,000 to 552,000 t during that period. Short (1993) noted that these estimates likely contain considerable error, given evidence that timber harvest activities substantially increase sediment concentrations (Nolan and Janda 1981, as cited in Short 1993) and given errors typically associated with suspended sediment estimates using rating curves (Ferguson 1986). The suspended sediment-discharge rating curve used in this analysis may therefore have been underestimated by up to an order of magnitude, suggesting that suspended sediment yield during the 1950–1986 period may have been as high as 5.53 million t (Short 1993).

Short (1993) assumed that bedload comprised 0.2–0.6 of total load, based on Redwood Creek data (Janda 1978). This suggests bedload yield of 139–830 t/km^2/yr, or total bedload yield of 55,000–332,000 tons for the 1950–1986 period. Applying a bedload:total load ratio of 0.5 indicates a bedload yield of 554 t/km^2/yr (220,000 t) (the same as suspended yield) for 1950–1986, and a total sediment yield of 440,000 t (range of 275,000 to 552,000 t, or 743–1492 t/km^2/yr).

Short (1993) also estimated net changes in sediment storage in the Cuneo Creek basin and in the lower 1.8 km of Cuneo Creek using a time-series of cross-section data for this reach. Short's storage estimates suggest that much of the accelerated hillslope sediment input during the 1950s and 1960s was stored in aggraded reaches of Cuneo Creek as of 1986, although roughly 240,000 m^3 (455,000 t) of sediment had eroded out of the lower 1.8 km of Cuneo Creek between the 1964 flood and 1986. This downstream transport of stored sediment out of Cuneo Creek, which reflected reduced hillslope inputs since the mid-1960s, contributed to aggradation and widening in lower Bull Creek (Short 1987). Aerial photographs of the upper Cuneo Creek basin show evidence of revegetation and reduced frequency of landslides, suggesting reduced hillslope sediment production (Short 1987). Despite this downstream transport, large amounts of sediment remained in storage as of 1986 and the pre-disturbance channel bed elevation still had not been attained (Short 1987).

Synthetic sediment budget for Bull Creek basin (LaVen 1987a)

LaVen (1987a) developed "synthetic" sediment budget estimates for the Bull Creek basin based on a combination of "known" and assumed process rates for different subwatersheds in the Bull Creek basin. This included estimates of hillslope inputs and bank failure rates in Bull Creek; monitoring of sediment storage changes through cross-section studies; 3 years of sediment yield data (1976–1979) from Bull Creek, and sediment yield data from Cuneo Creek (based on synoptic monitoring of the February 1986 storm). Bank failure rates were based on field measurements in lower and middle Bull Creek and lower Cuneo Creek and extrapolation of these data to other reaches; these rates were assumed to incorporate alluvial terrace contributions based on Kelsey (1977). Data from Kelsey (1977), with some modifications for the Bull Creek basin, were used to estimate earthflow input rates and hillslope contributions.

LaVen's synthetic sediment budget estimates, including estimates of sediment yield from hillslopes, alluvial areas, tributary streams and landslides for different portions of the Bull Creek basin, are summarized in Table 13. LaVen (1987a) estimated "present" sediment yield from the Bull Creek basin at 1.4 million t/yr, but did not indicate the time period for which this applies.

Table 13. Summary of LaVen's (1987a) "synthetic" sediment budget for Bull Creek basin.

Location	Area (mi^2)	Unit Rate		Total Rate (tons/yr)	% of Total
		tons/mi^2/yr	tonnes/km^2/yr		
Lower Bull Creek watershed	**12.9**	**5,700**	**2,000**	**73,500**	**5.25**
Middle Bull Creek watershed	**8.2**	**9,700**	**3,400**	**798,000**	**5.7**
Cuneo Creek watershed	**4**	**72,500**	**25,400**	**290,000**	**20.71**
Upper Bull Creek watershed	**15.9**	**60,200**	**21,100**	**956,700**	**68.34**
Burns Creek watershed	1.7	51,200	17,900	87,000	6.21
Slide Creek watershed	1.2	23,200	8,100	27,800	1.99
Panther Creek watershed	3.3	62,600	21,900	206,500	14.75
East Side Earthflow complex	3.3	106,700	37,400	352,200	25.16
Upper Bull Creek	1.9	48,400	17,000	92,000	6.57
other areas in Upper Bull Creek watershed	4.5	35,000	12,300	157,400	11.24
roads in middle and upper Bull Creek watershed				33,800	2.41
TOTAL	**41[a]**	**34,100**	**12,000**	**1,400,000**	**100**

a The drainage area reported by LaVen (1987a) of 41 mi^2 differs slightly from that calculated by the Stillwater Sciences GIS (43.3 mi^2).

LaVen (1987a) noted that large landslides were the largest sediment sources in the upper Bull Creek basin, especially in the sheared contact zone between the Coastal Belt and Yager terrains. He indicated that the second largest source in the upper Bull Creek was a 8.5 km^2-earthflow complex on the eastern side of Bull Creek that is drained by many small streams and that accounts for about 25% of total sediment yield in the Bull Creek basin. LaVen also cited the Panther Creek basin (15% of total in Bull Creek), including landslides, streambank failures, and terrace deposits, and the Burns Creek basin (6% of total in Bull Creek) as significant contributors of sediment in the upper Bull Creek basin. The Cuneo Creek basin contributes about 21% of total sediment yield in Bull Creek. LaVen indicated that the total annual contribution of sediment to Bull Creek from the road network was about 30,000 yd^3/yr (22,900 m^3/yr), which amounts to 1.5–2.0% of Bull Creek annual sediment yield.

LaVen (1987a) developed estimates of total annual sediment yields for a "hypothetical water year" (it is unclear whether this was intended to be equivalent to a hydrologically average water year) for 3 locations in the SFEB: Bull Creek at its mouth, and the SFE upstream and downstream of the Bull Creek confluence, with the latter representing sediment yield for the entire SFEB. These estimates were based on suspended sediment data for Bull Creek from 1976 to 1979 and for the SFE at Miranda station from 1981, combined with flow duration data for 1961–1982 (Bull Creek) and 1940–1982 (Miranda). LaVen (1987a) estimated total sediment yield for the 3 locations as follows: 10,390 t/mi^2/yr (3,640 t/km^2/yr) for the SFE upstream of

Bull Creek confluence; 35,000 t/mi^2/yr (12,270 t/km^2/yr) for Bull Creek, and 11,820 t/mi^2/yr (4,140 t/km^2/yr) for the SFE as a whole. These estimates assumed that about 3% of total load was bedload (LaVen 1987a), which is substantially lower than other estimates of the bedload fraction of total load in the SFEB. LaVen's estimates indicated that Bull Creek contributes about 18% of total yield in the SFEB, despite representing only 6% of the watershed's area (LaVen 1987a).

Studies of cross-section changes and bank erosion

According to LaVen (1987a), accelerated sediment inputs due to anthropogenic and climatic factors have triggered an aggradational cycle in Bull Creek since about 1950, causing bank failures and loss of old-growth redwoods along Bull Creek and the lower mainstem SFE. The causes of this aggradation are removed in time and space from the locations of bank failures, hindering the ability to prevent bank erosion (LaVen 1987a). In response to the changes in channel morphology in mainstem Bull Creek and associated impacts on old-growth redwoods, monitoring of channel cross-sections along the lower 8.5 km of Bull Creek has occurred since the 1960s. These studies have documented channel bed elevation changes and provide insight into changes in sediment storage and morphologic effects of basin recovery in Bull Creek (LaVen 1987b, Merrill and Vadurro 1999).

LaVen (1987b) reported on measurements of a series of cross-sections in the lower 8.5 km of Bull Creek in 1966, 1967, 1970, 1974, 1982, and 1986. These measurements indicated that between 1966 and 1982, the lower half of lower Bull Creek aggraded (i.e., bed elevation increased) and the upper half degraded (bed elevation decreased), which flattened the overall channel gradient in lower Bull Creek and reduced its sediment transport capacity (LaVen 1987b). In 1986, high flows caused additional aggradation (more than the total aggradation occurring from 1966 to 1982) (LaVen 1987b). A backwater effect from the mainstem SFE up Bull Creek likely contributed to deposition of large amounts of sediment in Bull Creek (LaVen 1987b). LaVen (1987a) also reports on a study of bank erosion in the mainstem SFE, indicating an average bank retreat rate of 1.4–1.5 m/yr (4.5–4.8 ft/yr) for the lower 63 km (39 mi) of the SFE.

LaVen's (1987b) study was updated by Merrill and Vadurro (1999). Downcutting of the channel bed (degradation) occurred between 1986 and 1998, by an average of 1.9 ft (0.58 m) at each cross-section. New anthropogenic channel disturbances did not occur during this period; Merrill and Vadurro (1999) suggest that downcutting therefore reflected the effects of basin revegetation and a reduction of sediment loading in lower Bull Creek. The 1997 flood caused aggradation in lower Bull Creek, with an average increase of 0.2 ft (6 cm) in thalweg elevation recorded at surveyed cross-sections. High flows during the 1997–1998 winter caused degradation (incision) through the 1997 deposits.

Merrill and Vadurro (1999) concluded that high magnitude flows (e.g., the 1997 event) cause aggradation in lower Bull Creek (partly because this is when backwater effects from the SFE occur), but moderate flows frequently scour the channel and transport sediment out of lower Bull Creek. This effect may also be related to reduced likelihood of landslide-triggering and sediment-producing storms being associated with moderate flows.

Studies of road erosion and other erosional processes

Limited data are available on road erosion rates in the Bull Creek basin. Many roads built for logging before incorporation into the State Park have been abandoned, and other roads are currently gated with limited access. The active road system is therefore substantially smaller than the overall road system. Road sites with potential erosion problems in the basin have been surveyed and described, including suggested prescriptions (Horns and LaVen 1986), but sediment production from these sites has not been quantified. The road survey by Horns and LaVen (1986) found that fillslope failures are common on roads built on steep slopes and adjacent to streams and that these failures often develop into debris torrents. Horns and LaVen (1986) noted that road fillslopes are susceptible to erosion because they consist of soil with low shear strength and cohesion. As noted above, LaVen (1987a) estimated that the total annual contribution of sediment to Bull Creek from the road network is about 30,000 yd^3/yr (22,900 m^3/yr), which amounts to 1.5–2.0% of Bull Creek's annual sediment yield. This includes a road length of 42.2 miles (67.9 km), for a unit rate of 800 t/mi of road/yr (500 t/km of road/yr) from road erosion.

Horns and LaVen (1986) indicated that streambank slides, which sometimes propagate upslope, were the most common type of mass wasting they observed in the Bull Creek basin. These slides, which are common along many tributaries to Bull Creek, have likely greatly increased in frequency because of logging and fires, including associated channel aggradation (which destabilizes the bases of hillslopes), heavy equipment disturbance, and loss of root strength (Horns and LaVen 1986). Deep-seated landslides also affect large portions of the Bull Creek basin, including several active earthflows showing evidence of recent movement (Horns and LaVen 1986). An episodic movement of a deep-seated landslide in Canoe Creek (just south of the Bull Creek basin) in spring 1984 buried a length of over 150 m (500 ft) of stream to a depth of 18–24 m (60–80 ft) about 1.6 km (1 mi) upstream of the SFE (Horns and LaVen 1986). Many inactive deep-seated landslides are also present in the Bull Creek basin (CDMG 1984). Gullies on deep landslides in the upper Bull Creek watershed, particularly where roads and skids collect surface flow, are also active erosion sites (Horns and LaVen 1986).

Evidence of recent accelerated movement of deep-seated landslides was observed by Stillwater Sciences in tributaries to Bull Creek, including Cow Creek, causing substantial impingement on channels and changes in channel morphology. This reactivation may have been related to seismic activity (an earthquake occurred near Bull Creek in 1992) and the 1996–1997 winter storms.

Discussion of Results for Bull Creek ISA

Results of the studies described above are summarized in Table 14. These results and those of the short-term suspended sediment yield measurements in Bull Creek (Fig. 1) indicate that sediment production in the Bull Creek basin is high compared to other ISAs and to the rest of the SFEB. The highest rate of sediment production was attributable to landslides (Fiori et al. 1999, Short 1993). Ratios of anthropogenic:total loading were not calculated in the Bull Creek studies, although Fiori et al. (1999) indicate that a large percentage of landsliding they documented was road-related. The Bull Creek results suggest that sediment production in the SFEB is highly spatially variable.

Table 14. Bull Creek studies, data summary table.

Subbasin	Process	Rate	Time Period	Source
Preacher Gulch	landslide sediment yield	154,601 yd^3 (1,062 $m^3/km^2/yr$; 2,017 $t/km^2/yr$)	1954–1997	Fiori et al. 1999
Preacher Gulch	surface erosion on lower PG road (light use)	9 yd^3/yr	current	Fiori et al. 1999
Preacher Gulch	surface erosion on abandoned roads	"very minor" (0–1 yd^3/yr)	current	Fiori et al. 1999
Preacher Gulch	road erosion sediment delivery (mass wasting)	0.007 $yd^3/yr/ft^2$ of road (assumes 22-ft road width)	1954–1997	Fiori et al. 1999
Cuneo Creek	total hillslope erosion	6.226 million tons (168,270 t/yr; 16,827 $t/km^2/yr$)	1950–1986	Short 1993
Cuneo Creek	landslides	5.4 million tons (2.8 million m^3) (143,780 t/yr; 14,378 $t/km^2/yr$)	1950–1986	Short 1993
Cuneo Creek	gullies	454,000 tons (7% of total)	1950–1986	Short 1993
Cuneo Creek	earthflows	372,000 tons (194,000 m^3) (9962 t/yr; 996 $t/km^2/yr$)	1950–1986	Short 1993
Cuneo Creek	sediment yield (assumes 0.5 bedload fraction)	1108 $t/km^2/yr$	1950–1986	Short 1993
Bull Creek	"synthetic" sediment yield	12,000 $t/km^2/yr$	undefined	LaVen 1987a

4.2.5 Discussion of Intensive Analysis Results

The results of the sediment source assessments in intensive study areas and of extrapolated results to the SFEB are presented in Tables 15, 16, and 16a and Figures 4 and 5. Comparison of results of the landslide assessments for the 1966-1981 and "current" periods for ISAs indicated a number of patterns. Inner gorge landsliding, including natural and road-related features, was substantially higher in the earlier period than in the recent period in all ISAs, including 3-fold higher in Sproul Creek and 4-fold higher in the Hollow Tree ISA. (Differences were even greater in the Tom Long ISA, but we have less confidence in the results because the estimates based on CDMG mapping for 1966–1981 appear anomalously high.) In contrast, rates of non-inner gorge landsliding (streamside natural, non-inner gorge road-related, upland management) were similar between periods in the Sproul Creek and Hollow Tree ISAs, with a slight reduction in Sproul and a slight increase in Hollow Tree between the previous and current periods. The influence of land use practices on these results is uncertain, but the results do suggest that wetter conditions (characteristic of the 1960s and 1970s) have a greater influence on landsliding in inner gorge areas, whereas non-inner gorge features may be less sensitive to climate variations. This conclusion is based on limited data and would need to be tested with additional mapping, field validation, and assessment of frequency of landslide-triggering storm events for different time periods.

Table 15. Summary of sediment source analysis results.

Intensive Study Area	Sediment Loading (t/km²/yr)		Anthropogenic:Total Sediment Input Ratio	
	Recent Period	1966–1981	Recent Period	1966–1981
Sproul Creek	552	866	0.76	0.51
Tom Long Creek	1,245	3,295	0.29	0.27
Hollow Tree Creek	693	918	0.57	0.62
South Fork Eel Basin	704	N/A	0.46	N/A

Table 16. Summary of sediment source analysis results for landsape unit-area sediment inputs (total annual input divided by ISA area) from each source category in each ISA per time period.

SEDIMENT SOURCE	INTENSIVE STUDY AREA AND TIME PERIOD					
	Sproul Creek		Tom Long Creek		Hollow Tree Creek	
	1981–1994	1966–1981	1981–1996	1966–1981	1978–1996	1966–1978
Earthflow toes and associated gullies	0	0	812	812	225	225
Inner gorge mass wasting, natural	81	287	0	641	12	96
Streamside (non-inner-gorge) mass wasting	44	129	32	903	54	23
Road-related mass wasting	37	18	35	29	112	186
Upland mass wasting	67	18	32	504	55	66
Road surface erosion	35	35	63	63	37	37
Road crossing mass wasting and gullying	264	264	219	219	176	176
Skid trail erosion	16	106	13	85	15	102
Soil creep	8	8	39	39	7	7
Total	**552**	**866**	**1245**	**3295**	**693**	**918**

Table 16a. Summary of sediment source analysis results for relative contribution (fraction of total) of each source category in each ISA per time period.

SEDIMENT SOURCE	INTENSIVE STUDY AREA AND TIME PERIOD					
	Sproul Creek		Tom Long Creek		Hollow Tree Creek	
	1981–1994	1966–1981	1981–1996	1966–1981	1981–1996	1966–1978
Earthflow toes and associated gullies	0.00	0.00	0.65	0.25	0.33	0.25
Inner gorge mass wasting, natural	0.15	0.33	0.00	0.19	0.02	0.10
Streamside (non-inner-gorge) mass wasting	0.08	0.15	0.03	0.27	0.08	0.03
Road-related mass wasting	0.07	0.02	0.03	0.01	0.16	0.20
Upland mass wasting	0.12	0.02	0.03	0.15	0.08	0.07
Road surface erosion	0.06	0.04	0.05	0.02	0.05	0.04
Road crossing and gully erosion	0.48	0.31	0.18	0.07	0.25	0.19
Skid trail erosion	0.03	0.12	0.01	0.03	0.02	0.11
Shallow soil creep	0.01	0.01	0.03	0.01	0.01	0.01
Total	1.00	1.00	1.00	1.00	1.00	1.00

These results indicate that in all ISAs, the overall unit-area sediment input in the earlier period was higher than in the recent period (Fig. 4), likely reflecting changes in climatic conditions and/or land use. Overall, the difference between periods may have been even greater than indicated here, because, for example, road erosion rates were likely higher in the earlier period but are assumed to be the same in our analysis. The difference between periods was especially large in the Tom Long ISA. In both periods, total sediment loading in the Tom Long ISA was higher and the anthropogenic contribution was lower than in the Hollow Tree and Sproul ISAs. This primarily reflects the effects of natural sediment production from earthflow toes and associated gullies in the Tom Long ISA, which is partly underlain by Melange terrain. Although we did not develop comparable results for the Bull Creek ISA, results of existing studies and those of short-term suspended sediment yield measurements in Bull Creek indicate that unit-area sediment production in the Bull Creek basin is the highest of all ISAs. In both periods, the unit-area sediment delivery is lowest in the Sproul Creek basin compared to other ISAs (Fig. 4), a difference that is partly attributable to the absence of active earthflows in the Sproul Creek basin.

In both the Hollow Tree and Tom Long ISAs, the ratio of anthropogenic to total sediment loading was about the same in both periods (Table 15, Fig. 5). In the Sproul Creek ISA, the ratio of anthropogenic to total inputs was higher in the recent period (0.76) than in the 1966–1981 period (0.51) (Fig. 5). This result may reflect the increase in timber harvest activities in the 1981–1994 period compared to the 1966–1981 period and reduced natural sediment production (from natural inner gorge and non-inner gorge streamside landslides) because of drier climatic conditions. The high anthropogenic contribution in the recent period in Sproul Creek is largely a function of the large amount of sediment production assigned to road crossing and gully erosion and therefore may be overestimated due to the high level of uncertainty associated with

Figure 4: Comparison of unit-area sediment inputs between subbasins and time periods

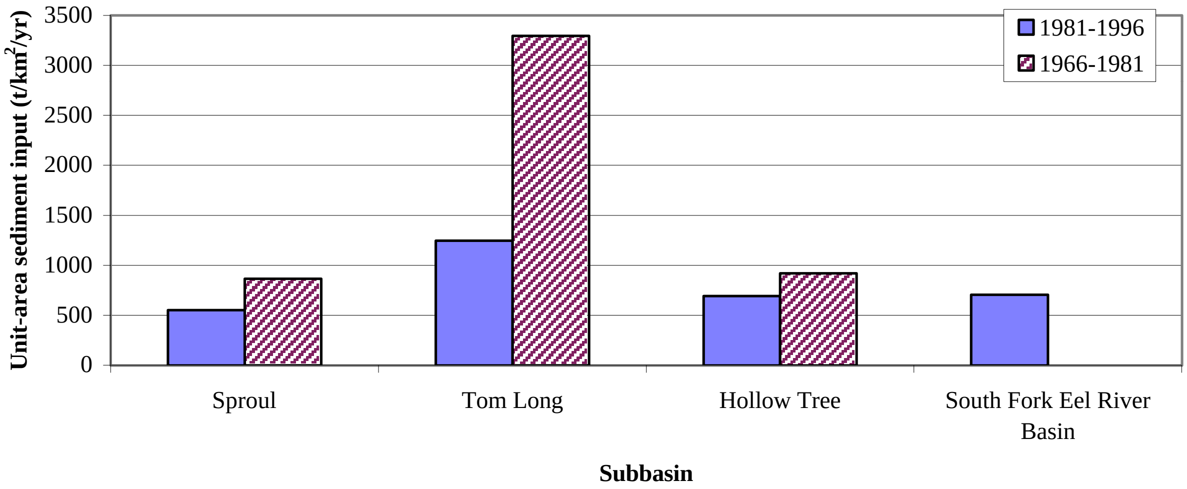
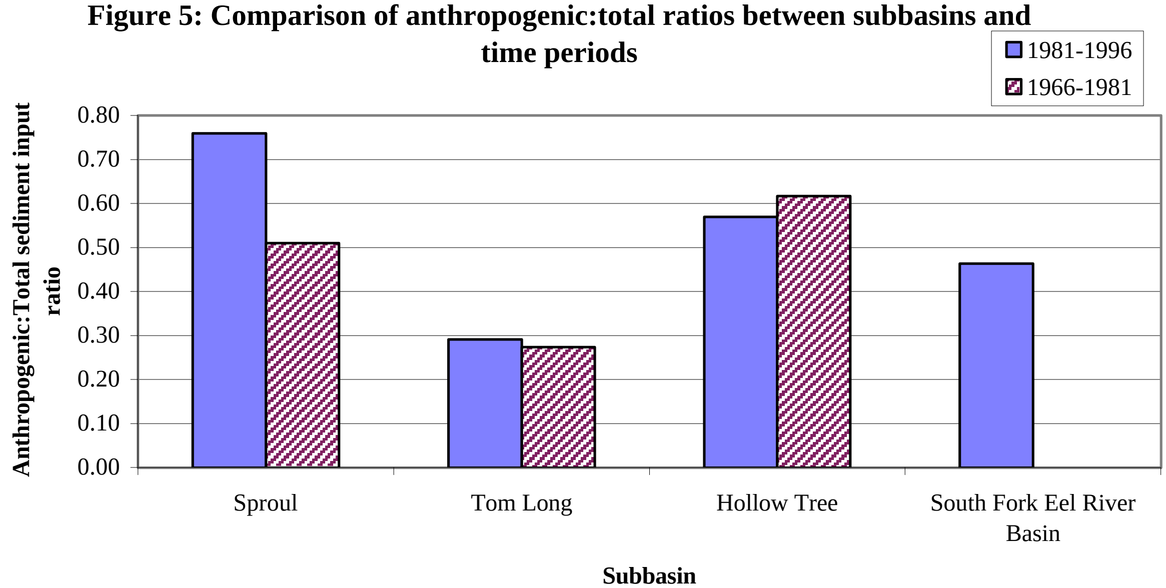


Figure 5: Comparison of anthropogenic:total ratios between subbasins and time periods



estimates for this source. Ratios of anthropogenic:total loading were not calculated in the Bull Creek studies, although Fiori et al. (1999) indicate that a large percentage of landsliding they documented was road-related.

Our analysis suggested several other differences in sediment delivery patterns between the recent and previous periods. Because sediment production from shallow landsliding (an episodic process) was lower in the recent period, “chronic” inputs from earthflows (in ISAs where active earthflows were mapped), as well as road crossing and gully erosion, contributed greater fractions of overall loading in the recent period than in the previous period. Road surface erosion rates, although assumed to be the same between periods, were actually probably higher during the previous period, given more intensive logging activities (with its associated higher levels of road use) and less stringent road maintenance and construction practices during the earlier period (no data were available on changes in road density with time in the ISAs). Some of the differences observed in comparisons between periods are attributable at least in part to the methods and assumptions used in our analysis. Road crossing and gully erosion is likely driven at least in part by episodic processes (e.g., large storm events), although our analysis assigned the same rates for this category to both time periods because we did not have data with which to assess this source for the 1966–1981 period. Earthflow sediment production is also likely episodic, as evidence suggests that earthflows are more active and move more rapidly after a series of wet years or in response to a large event such as the 1964 flood (e.g., Kelsey 1980). Our assumption of constant production from earthflows is an attempt to estimate an average flux over time from what is a discontinuous (episodic) process.

We tested the sensitivity of our overall anthropogenic:total ratios for all sediment sources in the ISAs to the assumptions about landslide causality outlined in Section 3.5.1 (Shallow Landslides) above. Ratios of anthropogenic:total loading incorporated the following criteria for estimating the relative proportion of natural versus anthropogenic landslides: (1) landslides associated with roads were identified as anthropogenic, (2) all non-road-related inner gorge slides were assumed to be natural, (3) all non-inner-gorge streamside slides were assumed to be natural if no road or timber harvest associations were visible, (4) all upland slides were assumed to be anthropogenic. We have the most confidence in causality assignments for road-related (including inner gorge and non-inner gorge) landslides as anthropogenic and for large (>about 1,000 m^2) inner gorge and streamside landslides as natural. Causality assignments for non-road related point slides are highly uncertain, however, and depend on the assumptions described above. If all landslides are assumed to be anthropogenic (including all inner gorge, non-inner gorge streamside, and upland features), this increases ratios for the recent period by 0.09 in the Hollow Tree ISA (i.e., from 0.57 to 0.66), 0.02 in the Tom Long Creek ISA (from 0.33 to 0.35), and 0.07 in the Sproul Creek ISA (from 0.79 to 0.86). Conversely, if all non-road upland slides are assumed to be natural (in addition to all non-road inner gorge and streamside slides), the anthropogenic:total ratio would decrease by 0.08 in the Hollow Tree ISA, 0.03 in the Tom Long ISA, and 0.11 in the Sproul ISA. This suggests that our assumptions about causality, which were adopted in the absence of detailed field surveys and data on land use history in areas where slides occurred, may cause errors on the order of plus or minus 0.1 in overall anthropogenic:total sediment input ratios in the ISAs. Given the many other assumptions and uncertainties in our analysis, this potential magnitude of error is not substantial.

4.3 1942 1965 Sediment Source Analysis

A USDA (1970) report provided sediment production estimates for the entire SFEB during the period from approximately 1942 to 1965. The USDA (1970) report assessed erosional processes in the Eel and Mad River basins, including the SFEB, providing information on sediment yields in the 1940s to 1960s. This report incorporated considerable field and aerial photograph studies and is valuable because it provides a source-specific analysis of the entire SFEB, including some estimates of causality. Streambank erosion and landslide data covered the period from 1942 to 1965, and sheet and gully erosion data were measured for the period from 1956 to 1965 and adjusted to the 1942–1965 period. A summary of the main findings of the report is provided below.

The 1970 USDA study estimated sediment yields for the following four categories: (1) sheet and gully erosion (including erosion from temporary roads, skid trails, landings, and other roads; sheet and gully erosion from logging, burning, grazing, deer, and other natural causes); (2) streambank erosion (defined as terrace material [alluvial] and inner gorge slopes [colluvial]); (3) landslides (includes failures larger than 200 ft [~60 m] in either dimension; smaller failures were incorporated in other categories); and (4) roads (includes only roads shown on USGS topographic maps [1:62,500]; other roads are considered under sheet and gully erosion). These categories differ from those used by Stillwater Sciences for the current conditions sediment source analysis; results are therefore not strictly comparable.

Table 17. Summary of USDA (1970) sediment source assessment for South Fork Eel basin, 1942–1965.

Source	Sediment Yield	Percent of Total	Anthropogenic:Total Ratio
	$m^3/km^2/yr$		
Sheet and gully	125.7	12%	0.56
Streambank erosion	494.4	47%	unknown
Landslides	429.4	41%	0.16
Roads	10.4	1%	1.0
TOTAL	**1060.1 (1951 $t/km^2/yr$)**	**100%**	**at least 0.14**

Stillwater Sciences converted the results presented in the USDA (1970) report from units of ac-ft/yr to $m^3/km^2/yr$ and $t/km^2/yr$ (1 ac-ft=1,234 m^3) in order to facilitate comparison with other studies (including our current conditions estimates for the SFEB). As in the rest of our analysis, we assumed a bulk density of 1.9 t/m^3 for colluvium and 1.4 t/m^3 for shallow soil (i.e., sheetwash erosion); these slightly differ from the bulk density suggested by USDA (1970) of 1.48 t/m^3. The 1970 USDA report found that the sheet and gully category accounted for 12% of total erosion in the SFEB (125.7 $m^3/km^2/yr$), streambank erosion accounted for 47% (494.4 $m^3/km^2/yr$), landslides accounted for 41% (429.4 $m^3/km^2/yr$), and roads accounted for 1% (10.4 $m^3/km^2/yr$). Total sediment yield was estimated to be 1,060.1 $m^3/km^2/yr$ (1951 $t/km^2/yr$) in the SFEB.

Sediment yield from sheet and gully erosion was calculated by causality, including erosion from logging, burning, grazing, deer, and other natural causes (Table 18). Anthropogenic sources added up to 70.5

$m^3/km^{2/}yr$, or 56% of the sheet and gully erosion total, while deer and other natural sources account for 55.2 $m^3/km^2/yr$, or 44% of the total of 125.7 $m^3/km^{2/}yr$. The USDA (1970) report also estimated that erosion control programs could reduce the anthropogenic contribution to sheet and gully erosion from 56% to 28%.

As part of the sheet and gully erosion assessment, sediment yields from natural grasslands and areas converted to timberlands were also estimated. Grazing on privately owned grasslands (range) within the Eel and Mad river basins resulted in an average (1942–1965) sediment yield of 197.5 $m^3/km^{2/}yr$ from sheet and gully erosion, with slightly higher rates estimated for converted timberlands (226.3 $m^3/km^{2/}yr$).

Table 18. Summary of erosion rates for sheet and gully erosion in the South Fork Eel basin as presented in USDA (1970) report.

Sheet and gully erosion source	**Rate ($m^3/km^2/yr$) (1942–1965)**	**Ratio Anthropogenic:Total**
Logging	29.7	1.0
Burning	2.1	1.0
Grazing	38.7	1.0
Deer	19.3	0
Natural	35.9	0
Total	**125.7**	**0.56**

Streambank erosion was also estimated by USDA (1970), with rates and average bank height per channel order presented. Bank erosion was estimated by comparing sample stream reaches on aerial photographs from 1965 with photographs from 1941, 1944 of 1948 and estimating the volume eroded in sample reaches during that time. This analysis, which included erosion of alluvial banks and streamside-landslide toes (colluvial inputs) in the bank erosion category, indicated total bank erosion of 494 $m^3/km^2/yr$ over a total channel length of 2,873 km (1,785 miles) in the SFEB, with the largest contribution attributed to second-order channels. This amounts to 47% of total erosion in the SFEB. USDA (1970) indicated that the anthropogenic contribution to streambank erosion could not be determined but land uses had likely accelerated streambank erosion. The USDA (1970) report therefore does not account for causality of approximately half of the total sediment load in the SFEB for the 1942–1965 period.

Erosion rates from large landslides (greater than 60 m [200 ft] in either dimension) were estimated by multiplying an estimated annual rate of movement of active slides “by the cross-sectional area of the exposed or eroding face to give the estimated annual volume of sediment yielded by the landslide" (USDA 1970, p. 63-73). This was performed for the 1941, 1944, 1948, and 1965 aerial photograph series, resulting in average landslide sediment production rate of 429.4 $m^3/km^2/yr$. USDA (1970) assigned causality to landslides, concluding the 16% of landslide sediment yield was caused by anthropogenic activities in the Eel and Mad river basins as a whole. Slides smaller than 60 m (200 ft) in either dimension were classified as sheet, gully, road, or streambank erosion.

Road erosion rates were calculated only for roads shown on USGS topographic quads (1:62,500) and in national forests (which do not occur in the SFEB); erosion from temporary roads, skids, landings, and other roads not shown on the maps was considered as part of sheet and gully erosion. Sediment yield from roads included landslides smaller than 60 m (200 ft) in either dimension and gullies on cutbanks, fillslopes, and road surfaces. The USDA (1970) report indicated that in the SFEB, USGS topographic maps (1:62,500) indicated the existence of 151 km (94 mi) of medium-duty road, 216 km (134 mi) of light-duty road, and 410 km (255 mi) of unimproved road. Average annual sediment yield rates for roads in the SFEB were about 10 $m^3/km^2/yr$ (15 ac-ft/yr) (USDA 1970). The rates presented are very low and may underestimate road-related sediment inputs. The USDA (1970) report noted that inclusion of road-related landslides and streambank erosion in the road erosion category would increase its contribution to total sediment yield to 3% (compared to 1% without inclusion of such erosion).

USDA (1970) also reported sediment yield estimates for the Van Duzen River basin (part of the Eel River basin), which can be compared with those of Kelsey (1977) for the upper Van Duzen basin from 1941 to 1975. Kelsey's (1977) results were based on extensive field work and aerial photograph analysis and are therefore likely reasonably accurate. Sediment yield estimates from these two analyses were similar: USDA (1970) indicated total yield of about 2,800 $t/km^2/yr$ in the Van Duzen River basin from 1942 to 1965, while Kelsey (1977) reported a yield of about 3,400 $t/km^2/yr$ in the upper Van Duzen basin from 1941 to 1975. The similarity between these numbers increases our confidence in the USDA (1970) results for the SFEB.

The overall ratio of anthropogenic to total sediment inputs cannot be determined from the USDA (1970) report, because causality of streambank erosion, which accounts for nearly half of all loading, is unknown. If none of the streambank erosion is assumed to be anthropogenic (which the USDA report indicates is unlikely to be the case), the overall anthropogenic:total ratio would be 0.14, providing a minimum estimate. If half of the streambank erosion is assumed to be anthropogenic, the anthropogenic:total ratio would be 0.37.

4.4 Extrapolation of Results Across SFEB for 1981 1996

Stillwater Sciences extrapolated the results of sediment source assessments for ISAs to the entire SFEB based on GIS/DTM methods in order to develop SFEB-wide estimates of sediment loading and anthropogenic:total ratios. The methods and results of this extrapolation are discussed below and are summarized in Table 19.

Table 19: South Fork Eel Basin, 1981–1996: sediment source analysis results (totals have been rounded)

Sediment Source	Total sediment input (t/yr)	Landscape unit-area sediment input (t/km^2/yr)	Fraction of total	Coarse sediment input (t/yr)	Fine sediment input (t/yr)	Fine: total ratio	Natural input (t/yr)	Anthropogenic input (t/yr)	Anthropogenic: Total sediment input ratio
Earthflows toes and associated gullies	478800	269	0.38	143640	335160	0.7	478800	0	0
Shallow landslides, natural	132500	74	0.11	39750	92750	0.7	132500	0	0
Shallow landslides, anthropogenic	216200	121	0.17	64860	151340	0.7	0	216200	1
Road surface erosion	67512	38	0.05	0	67512	1	0	67512	1
Road crossing and gully erosion	276500	155	0.22	82950	193550	0.7	0	276500	1
Skid trail erosion	21534	12	0.02	2153.4	19380.6	0.9	0	21534	1
Soil creep	62980	35	0.05	18894	44086	0.7	62980	0	0
Total	**1,256,000**	**704**	**1**	**352,000**	**904,000**	**0.72**	**674,000**	**582,000**	**0.46**

Earthflow toes and associated gullies

Stillwater Sciences estimated the total length of earthflow toes abutting stream channels in the SFEB using the CDMG GIS coverage and USGS blueline stream channel coverage. Translational/rotational slides are assumed to be dormant throughout the SFEB. Given that toes form in higher-order channels, the USGS channel coverage was sufficient for this query. The total length of earthflow toe banks was estimated as 28 km. Applying an average bank height of 9 m, movement rate of 1 m/yr, and bulk density of 1.9 t/m^3 (28,000 m x 9 m x 1 m/yr x 1.9 t/m^3) (these assumptions are discussed in Section 3.5.2 above) results in delivery of 478,800 t/yr from earthflows and associated gullies in the SFEB.

Shallow landslides

Estimates of shallow landsliding across the SFEB were developed based on results of mapping in ISAs (Hollow Tree, Tom Long, Sproul) and extrapolation using the SHALSTAB shallow landslide hazard model. In these ISAs, all landslides were identified by log q/T category using a GIS overlay of 30-m SHALSTAB results (because 10-m data were not available for the SFEB as a whole) with digitized landslides, and the total area of landslides per log q/T class was determined in each ISA. These landslide areas per SHALSTAB class were converted to estimates of average annual unit sediment flux from each SHALSTAB class, and unit-area production rates for each SHALSTAB class were applied across the area of that class in the SFEB. This calculation resulted in total landslide sediment inputs of about 348,700 t/yr, all of which occurs in the Coastal Belt and Yager terrains. This extrapolation method accounts for variations in topography and assigns the highest potential sediment production rate to those SHALSTAB classes in which most mapped landslides occur (i.e., those with log q/T values of less than –2.5). Additional details on the use of SHALSTAB in extrapolating shallow landslide results are provided in Appendix A.

We also estimated the anthropogenic to total ratio of sediment delivery from landslides for the “current conditions” period based on an average of ratios estimated for ISAs of 0.62. This average is based on ratios of 0.72 in the Hollow Tree ISA (1978–1996), 0.46 in Sproul Creek (1981–1994), and 0.68 in the Tom Long ISA (1981–1996). Applying an anthropogenic:total ratio of 0.62 suggests landslide sediment production from anthropogenic causes (mainly roads) of about 216,200 t/yr in the SFEB from 1981 to 1996.

Road crossing and gully erosion

Stillwater Sciences combined roads coverages from CDF/FRAP and USGS (1:100,000), resulting in a total GIS length of roads in the SFEB of 3,359 km, which suggests an average road density of 1.88 km/km^2. The total road length was multiplied by the linear rate of road crossing and gullying erosion developed for the ISAs of 82 t/km/yr (based on field surveys in the Hollow Tree, Tom Long, and Bull Creek ISAs), resulting in total delivery of 276,500 t/yr from road crossing and gully erosion in the SFEB. No adjustment was made to subtract out ridge roads from total road length, as was done in the ISAs, because of the overall underrepresentation of road length on the CDF/FRAP and USGS coverages.

Road prism sheetwash

In order to extrapolate road surface erosion results generated for ISAs by SEDMODL, an average of the linear surface erosion rates estimated in the ISAs was calculated. This average linear rate, 20.1 t/km/yr, was applied to all roads in the SFEB, with a total road length of 3,359 km determined from the CDF/FRAP and USGS coverages. This calculation resulted in a road surface erosion rate of 67,500 t/yr, which is likely a substantial underestimate because of missing roads on the GIS roads coverages and the likelihood that SEDMODL underestimates the percent of road length that delivers sediment to channels.

Skid trail erosion

The unit-area sediment production from skid trails (16 t/km^2/yr) estimated by MRC for lands in the Hollow Tree ISA for the recent period (defined by MRC as 1984–1996) was extrapolated across areas in the Coastal Belt and Yager terrains in the SFEB, which have a total area of about 1,346 km^2. We assumed that no skid trails are found in the Melange Matrix terrain. This calculation suggests total production from skid trails of 21,534 t/yr under current conditions.

Soil creep

Soil creep inputs for the SFEB were calculated by two methods. For shallow soil creep, an average unit-area rate based on SEDMODL estimates for ISAs of about 9 t/km^2/yr was calculated. This rate was applied to all areas in the Coastal Belt and Yager terrain (1,346 km^2), where shallow creep is a chronic process. This resulted in total production from shallow creep of 11,844 t/yr. This is likely an underestimate, although the effect on the overall budget is likely small. For mantle creep, which is predominant in Melange Matrix areas, the unit-area mantle creep rate calculated by SEDMODL for Melange areas in the Tom Long ISA, 146 t/km^2/yr, was used for extrapolation. Application of this rate across the Melange terrain (350 km^2) results in total mantle creep production of 51,134 t/yr. Combined with the shallow creep estimate from the Coastal Belt and Yager terrains, this suggests total soil creep production of 62,980 t/yr in the SFEB.

Summary of results for SFEB, 1981–1996

This analysis concluded that average sediment delivery in the SFEB from 1981–1996 was 704 t/km^2/yr, with a ratio of anthropogenic:total loading of 0.46. The unit-area sediment delivery rate, which is based on extrapolation of results from the Hollow Tree, Tom Long, and Sproul Creek ISAs, may be most representative of the SFEB upstream of the Bull Creek confluence. This is because Bull Creek, which is not accounted for in the SFEB-wide estimates, appears to have substantially higher unit-area sediment yield than the rest of the SFEB. Considerable spatial variability in sediment loading is likely to exist in the SFEB, with the highest loading occurring in inner gorges along the mainstem, in the Bull Creek basin, and in areas underlain by Melange terrain. Reducing sediment loading in the SFEB to a single number (about 700 t/km^2/yr) is therefore not particularly meaningful, as it does not reflect the substantial spatial variability in sediment fluxes.

5. DISCUSSION

As noted above, our analysis concluded that average sediment delivery in the SFEB from 1981–1996 was about 704 t/km^2/yr, with a ratio of anthropogenic:total loading of 0.46. Given the uncertainties in our analysis, it is reasonable to round these values to 700 t/km^2/yr and 0.5. These data suggest that under current conditions and current land uses, there is a significant anthropogenic contribution to total sediment loading. Multiplying the sediment loading estimated for the current period (700 t/km^2/yr) by the natural fraction of this loading (0.5) suggests that in the absence of land uses, sediment loading in the SFEB would have been about 350 t/km^2/yr during the 1981–1996 time period. This number is very low for a basin with the topographic, climatic, and tectonic characteristics of the SFEB, which has been reported to have one of the highest sediment yields in the United States (e.g., Brown and Ritter 1971, Cleveland 1977). This suggests that our sediment source assessment may have substantially underestimated total sediment inputs, perhaps due to the omission of sources such as alluvial bank and terrace erosion.

Although we did not assess SFEB-wide loading in the 1966–1981 period, the differences between that period and the more recent period in the ISAs, as well as limited suspended sediment yield data from the SFE near Miranda gauge (Table 3), suggest that sediment yield during this period was likely in the range of 1,000–1,500 t/km^2/yr (i.e., nearly double the current period). Average annual runoff was about 10% higher in this period than in the more recent period, which may have accounted for part of this difference. The sediment yield estimated for the SFEB from 1942–1966 by USDA (1970)—1,950 t/km^2/yr—was almost three times higher than our estimate for the 1981–1996 period. Average annual runoff was about 10% higher in this period than in the more recent period, which may have accounted for part of this difference. The period assessed by USDA (1970) included the 1964 flood, which triggered substantial mass wasting and likely accounted for a large proportion of the sediment yield during this period (e.g., Lisle 1990). The 1942–1965 period was also characterized by intensive logging practices, particularly following World War II. Despite the occurrence of the 1964 flood, average annual runoff during this period was about the same as in the 1981–1996, according to analysis of discharge records from the SFE at Miranda gaging station. The USDA (1970) analysis used different methods than applied by Stillwater Sciences for the two more recent periods and incorporated substantially more field and aerial photograph data.

This sediment source assessment for the SFEB contains considerable uncertainty, given the many assumptions, the limited time for field surveys, and the focus on a subset of the basin (ISAs). These constraints reduced our ability to differentiate between effects of various land management practices on geomorphic processes in the ISAs. The potential effects of some land uses (e.g., dispersed residential use) are poorly accounted for, while others (e.g., grazing) are not accounted for at all. Grazing and the replacement of native perennial grasses by European annuals with shallower roots may have increased gullying of grasslands in melange areas (Kelsey 1980), while residential use, which is associated with year-round road traffic and often with poor road maintenance practices, is likely an important contributor of chronic road surface erosion inputs.

These results were compared to those of other sediment source analyses conducted in the region. In the South Fork Trinity River basin, Raines (1998) estimated average sediment delivery of 370 t/km^2/yr (1,053 t/mi^2/yr) from 1944 to 1990, with a ratio of anthropogenic to total loading of 0.28. For the 1975–1990 period, Raines indicated loading of about 180 t/km^2/yr (503 t/mi^2/yr) and a ratio of about 0.4. In the Redwood Creek basin, average sediment delivery of 1,720 t/km^2/yr (4,900 t/mi^2/yr) from 1954 to 1980 was estimated based on extensive research conducted in that basin (Redwood National and State Parks 1997). Although no ratio was identified, the Redwood Creek results indicated that 60% of total loading was "controllable." If these inputs are assumed to represent the anthropogenic contribution, this suggests a ratio of 0.6 for the Redwood Creek basin. In the Garcia River basin, the following ratios of anthropogenic to total loading were estimated for various time periods: 0.70 in 1956–1965, 0.65 in 1965–1978, and 0.58 in 1978–1996 (M. O'Connor, pers. comm., 1999). Average overall loading estimated for the Garcia River basin from 1956 to 1996 was about 420 t/km^2/yr (1,200 t/mi^2/yr).

Although our sediment source assessment for the SFEB used different methods and time periods than the analyses of other river basins described above, all of these analyses indicate that the anthropogenic contribution to overall loading has been approximately 0.3 to 0.6 of the total in recent decades. The anthropogenic ratio we estimate for current conditions in the SFEB, about 0.5, is within this range. While these numbers (total loading and/or ratios) may not actually be significantly different from each other, it is reasonable to conclude that in recent times sediment contributions due to landuse accounts for about 30 to 60% of the total sediment loads in the SFEB and other northern coastal California rivers.

Our results indicate total unit-area loading (700 t/km^2/yr) from 1981–1996 that is nearly twice that of the South Fork Trinity River basin from 1944 to 1990 and nearly 4 times as large as loading from 1975 to 1990 (Raines 1998). The total loading in the SFEB during the current period has been less than that from Redwood Creek (1,720 t/km^2/yr) for the 1954 to 1980 period, although the SFEB results for 1942–1965 (1,950 t/km^2/yr; USDA 1970) and our rough estimate of loading from 1966 to 1981 (1,000 to 1,500 t/km^2/yr) in the SFEB are similar to the Redwood Creek results.

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